Development, Construction and Testing of Prototype Accessories for Automation of a Down-the-Hole Drill

Final Report

by

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Executive Summary

This document is the final report for the CANMET funded project titled 'Development, Construction and Testing of Prototype Accessories for Automation of a Down-the-hole Drill', DSS File No. 06SQ.2340-4-9339. The project seeks to improve the cost effectiveness of Down-the-Hole drilling by introducing instrumentation/automation to four aspects of the drilling process. These are: to allow quick and accurate setting of the drilling equipment; to track the deviation of the drilled hole from the required hole as it is being drilled; to log setup and drilling parameters for later analysis; and, to control drilling parameters in order to optimize drill penetration. Prototype accessories capable of performing these functions have been developed, constructed and field tested.

The project has introduced a number of new technologies to the demanding mining environment which have enhanced the original project scope. At the heart of the system is a controller built around a general-purpose computer. In contrast to more typical PLC technology, this controller has the capability of executing a wide variety of complex algorithms. Beyond simple PDI servo control of drill pressure and rotation, features such as automated soft letdown of the drill string after adding a drill rod will increase bit life and hence productivity. The computational capabilities of the system have allowed a novel and simple approach to the surveying of the rig position and subsequently the capability of setting up with complex mast angles, resulting in increased productivity and accuracy. This design approach establishes a link to future control technologies such as expert systems now emerging for use by the mining industry. Despite the high level of technology, no problems were encountered with survivability in the mining environment. The interactive operator display panel substituted the more typical

bulky array of confusing buttons and lights with a small portable display and 'function keys'. Clear messages and instructions as well as numeric readout of gauges were displayed only as required. Despite the characteristics of the environment and unfamiliarity of the operators with such 'high-tech' equipment, the ergonomically sensible design was in fact quickly learned and well received by the operator during tests. In order to instrument the rig, sensors for penetration rate and indexing angle/rate are crucial to the logging and control of the drilling process. Devices with the required ruggedness are not currently available on the market. VADEKO has developed a set of very rugged sensors that meet the functional and environmental requirements by adapting some leading-edge technologies to the mining environment. The instrumentation of the drill rod has introduced technology to the area of the percussive drill itself and shown that sensitive electronic equipment can survive such extreme conditions.

Beyond the introduction and proving of new technology in a mining environment, the prototype system designed by VADEKO is actually very close to a commercializable unit. As a result of the field tests, a number of modifications and improvements to various components have been identified, but the configuration and principles are basically proven and will not require major re-engineering to make fully commercializable. The system was also designed as a generic retrofit package, and as such requires only a limited amount of additional engineering to adapt to any DTH drill rig currently on the market.

The system was targetted for and tested on a Continuous Mining Systems (CMS) CD-90, in cooperation with INCO Mines Research. Overall, a substantial amount of success was achieved in the limited amount of field testing that was made possible. Further tests are likely to be conducted to test the technology to its limits.

Some results of the field tests are inconclusive because actual operating test conditions varied from those established in the problem definition. Factors such as drill air pressure and moisture content were outside the design specifications. Either the design requirements should be amended or the tests conducted in accordance with the defined design conditions. Automated drilling requires a more complex model than that of simply maintaining a constant rotation rate and feed pressure. A number of design improvements to subsystem components have been identified that would improve the system reliability.

Sommaire Executif

Le présent document est le rapport formel du projet financé par CANMET et intitulé "Mise au point, construction et essai de prototypes d'accessoires pour automatisation d'un équipement de forage travaillant en fond de trou", Dossier du Ministère des approvisionnements et services No. 06SQ.2340-4-9339. L'objectif du projet est l'amélioration de l'efficacité économique des travaux de forage par équipement de fond de trou par utilisation d'instruments et automatisation dans les quatre aspects du processus de forage. Il s'agit de permettre un positionnement rapide et précis de l'équipement de forage; suivre la déviation de trou foré par rapport à la trajectoire recherchée à mesure de la progression de forage; d'enregistrer les paramètres de réglage initial et de forage pour analyse ultérieure; et de contrôler les paramètres de forage pour pouvoir optimiser la pénétration du trépan. On a mis au point, fabriqué et testédes prototypes d'accessoires capables de remplir ces fonctions.

Le projet a permis l'introduction de plusieurs nouvelles technologies dans le rigoureux environnement minier, ce qui a augmenté l'ampleur du projet. Le coeur du système est un contrôleur élaboré à partir d'un ordinateur d'application générale. À la difference de la technologie PLC plus typique, ce contrôleur a la capacité d'exécuter une grande variété d'algorithmes complexes. Au-delà du simple servo contrôle PDI de la rotation du tube de forage et de la pression qu'il exerce, des caractéristiques comme l'automatisation du relâchement en souplesse de la lance après l'addition d'une nouvelle section de lance amélicrent la longévité de la pointe de forage et ainsi la productivité. Les capacités de calcul du système ont apporté une simple et nouvelle approche à l'observation de la position du système de forage, et ultérieurement la possibilité d'ajuster l'angle d'inclinaison du mat, ce qui produit une amélioration de la productivité et de la précision. Cette approche de la

conception établit un lien avec des technologies de contrôle futures, telles gue les "systemes experts" qu'on développe actuellement à l'intention de l'industrie minière. Malgré le niveau technologique élevé, on n'a rencontré aucun problème au sujet de la capacité de survie de l'équipement dans l'environnement minier. Au niveau de l'opérateur, le panneau classique convert de boutons et voyants-témoins est remplacé par un petit afficheur interactif portatif et des touches de fonction. Le système affiche des instructions et des messages clairs tels que les valeurs numériques fournies par les divers instruments de mesure, seulement lorsque cela est nécessaire. Malgré les caractéristiques de l'environnement et le manque de familiarité des opérateurs avec un équipement d'une telle sophistication, les opérateurs ont fait bon accueil lors des essais à cet équipement de conception ergonomique, et ils ont rapidement appris à s'en servir. Lors de l'installation des instruments de mesure, les capteurs de détection de la vitesse de pénétration et de la variation angulaire sont les éléments cruciaux du processus de survie et du contrôle du processus de forage. On ne trouve pas sur le marché les appareils possédant la robustesse nécessaire. VADEKO a mis au point une série de capteurs très robustes qui satisfont les critères fonctionnels et les critères imposés pas l'environnement, en adaptant certaines technologies de pointe à l'environnement minier. Le système d'instrumentation de lances de forage a permis d'introduire la technologie dans le domaine du forage par percussion, et l'expérience a enseigné qu'un équipement électronique sensible peut survivre dans des conditions très rigoureuses.

Au-delà de l'introduction et de l'essai d'une nouvelle technologie dans un environnement minier, le système prototype conçu par VADEKO est en fait très proche d'une unité commercialisable. À la suite des essais sur le terrain on a identifié plusieurs modifications et améliorations utiles pour divers composants, mais les principes essentiels de la conception sont établis; il ne sera pas nécessaire de faire d'importants

travaux d'ingénierie pour rendre l'unité totalement commercialisable. Le système a également été mis au point comme système de modernisation générique, et à ce titre il ne nécessite que pue de travail d'ingénierie additionnel pour l'adaptation à tout équipmement de forage en fond de trou actuellement disponible sur le marché.

Le système était destiné à un système d'abattage continu (CMS) CD-90, et on l'a testé dans ces conditions en coopération avec INCO Mines Research. Dans l'ensemble, on a obtenu un succès substantiel à l'occasion des tests limités qu'il a été possible d'exécuter. De plus, il est probable qu'on effectue d'autres tests pour évaluer la technologie jusqu'à ses limites.

Certains résultats des essais effectués n'ont pas été concluant parce que les conditions effectives des essais étaient différentes de celles établies dans la définition du problème. Par exemple, les spécifications de conception ne tenaient pas compte de facteurs tels que pression et teneur en humidité de l'air comprimé d'alimentation de l'équipement. On devra donc amender les spécifications de conception, ou effectuer les essais en conformité avec les conditions de conception telles qu'elles sont definies. L'abattage automatisé nécessite un modèle plus complexe que le simple maintien de la vitesse de rotation et de la pression d'alimentation à des valeurs constantes. On a identifié plusiers possibilitiés d'amélioration des composants des sous-systèmes, lesquels permettraient d'améliorer la fiabilité du système.

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1 Introduction

Down-the-hole drills (DTH) are widely used in underground hardrock bulk mining methods. Although they are the preferred drills, further development is required with respect to accuracy of setting, on-line azimuth and deviation reporting, and drill performance optimization. Additions or improvements in these areas would lead to enhanced stope productivity, less dilution, improved performance, greater recovery, and the use of larger stope heights.

Several bulk mining methods are presently in use, but are based on the same basic primary concept. The DTH drill is operated from a drilling sill. Most often the hole direction is in the plane of the deposit and parallel to the dip. The distance between individual holes and rows depends upon the width of the ore body, the blasting technique, the fragmentation required and fragmentation characteristics of the ore.

This contract was for the development of a DTH Automation System which accurately locates, in real time, the bit location in terms of collar and drill pattern coordinates. It was not concerned with the development of a DTH drill bit guidance system which was beyond the scope of this contract.

To realize the potential economies that can result from accurate drilling control, the following must be achieved:

1. accurate placement of the drill at the planned collar and alignment of the drill mast with the predetermined drill hole azimuth and inclination; and,

2. early detection of the unacceptable hole deviation and drill rod retraction to avoid the costly drilling of holes that cannot be used.

To fulfill these aims, the resulting statement of work for this contract reads:

' The contractor shall design, construct and test prototype accessories for DTH drills, including retrofit capability:

1. digital instrumentation for accurate positioning and aligning of the DTH drill;

2. sensors, instrumentation and related telemetry devices/techniques for measuring and recording azimuth and deviation of the borehole on an on-line basis;

3. sensors, microprocessor and decision making logic/software to sense various drilling parameters to optimize drilling function, making its performance independent of variation encountered during drilling including a rod counter/depth recorder;

4. an output device to make available all pertinent data/information recorded or generated by the sensors on instrumentation, in a useable format.'

2 Project Overview

The design criteria used in the developemnt of the DTH drill accessories were the following:

- retrofit capability;
- machine independence;
- modular;
- interchangeability;
- simplicity (for operators); and,
- digital information retrieval for engineers.

The system has been designed for retrofitting to the following drill machines:

- Cubex 4150 Unitized
- TRW 6200 Megamatic
- CMS 90
- CMS 360
- Atlas Copco

Figure 2.1 is a block diagram of the DTH Drill Automation System. It consists of an Instrumented Rod Subsystem (IRS), a Controller Subsystem (CS), a Drill Hydraulic Subsystem (DHS), and a Rig Setup Subsystem (RSS). At the heart of the total system is the CS. It contains the controller and software which processes the sensor data from each subsystem and generates the control outputs. The RSS, IRS, and DHS perform the functions required by paragraphs 1, 2 and 3 of the work statement respectively. The fourth part of the work statement is fulfilled by a removeable Bubble Memory device which is housed within the CS. Also grouped with the CS is the Operator Display Assembly (ODA).

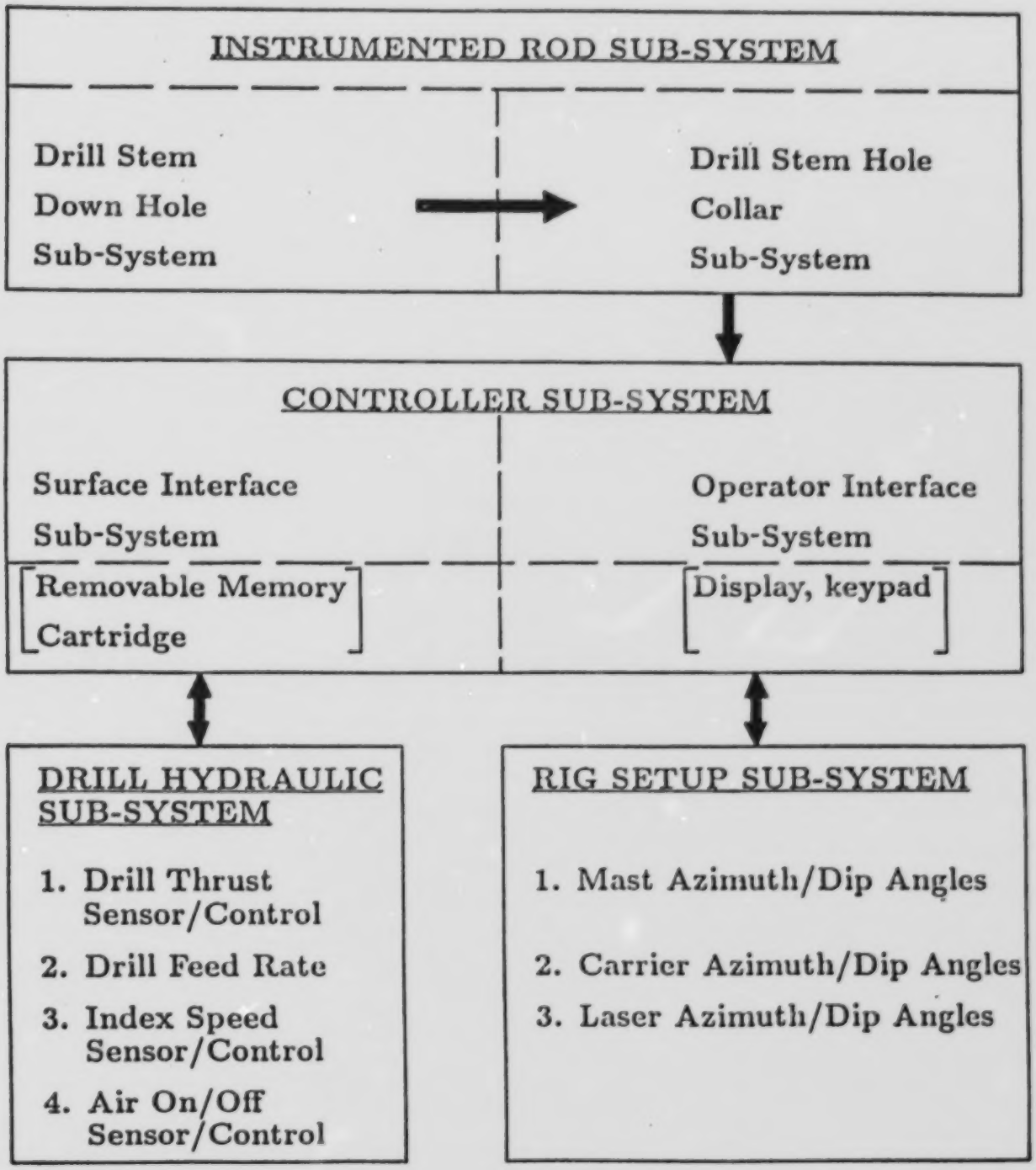


Figure 2.1

DTH Drill Automation System

The system has been designed for minimum interdependence between the sub-systems performing the four required functions. If one sub-system is not functional, then the others can still be used to a maximum extent. Only the CS (excluding the bubble memory) must be functional in all cases.

3 Field Trials and Results

A total of five field trips have been undertaken to test the validity of the concepts and hardware designed. The initial test plan and purpose was as follows:

1. approximately 5-10 days on surface to verify operation of the system under actual drilling conditions (field debug).

2. approximately 2-3 days on surface to examine effect of drill rod used by CD-90 on microwave transmission.

3. approximately 5 days underground to test system under actual operating conditions.

In practice, it was not possible to follow the test plan to any great extent. Mining equipment malfunctions, weather conditions on surface, and the logistics of planning tests in a mining environment quickly eroded the time available for field tests.

The results of the five trips are summarized as follows:

Trip 1: incurred 4 days delay due to a problem with trucking company delivering the rig to INCO, and subsequent arranging of a suitable test site for the rig. Initial checkout and demonstration of the rig was performed. Use of a booster compressor for which the system was not designed caused failure of the automatic air control system. Problems with manual drilling appeared to be related to the loose rock of the test site, but it was later discovered the hammer and bit were in need of repair.

Trip 2: A brief trip to check rig status after it was used

for several days in VADEKO's absence for production revealed the feed and rotation sensors had failed. These were removed for analysis, which resulted in small design improvements.

Trip 3: Trip to install improved sensors and continue debug found the rig in the shop undergoing major modifications (such as narrowing wheelbase to fit in cage and replacement of a failed feed cylinder). The sensors were replaced and checked, but no further debug was possible.

Trip 4: With the rig now underground,both in an attempt to speed-up field testing and due to harsh surface weather conditions, the underground test site still did not have all the required items. The following two days were spent at a different site in an attempt to test the instrumented rod by itself on a pre-drilled surveyed hole. Although this would indeed have yielded a great amount of information about the microwave transmission characteristics and accuracy of the device, equipment malfunctions in the mine and lack of power at the test site resulted in very little data indeed.

Trip 5: Seven days were spent underground with the modified drill rig, and with everything required for the test finally in place. The resulting debug cycle was extremely fruitful and accounts for the vast majority of results and data detailed below. The field trip was brought to an end primarily by lack of time remaining until the end of the contract, but also as is explained below, by the failure of the drill rod carrying the instrumentation.

During the test cycle, there were no failures of the controller, display, or RSS. Only three problems causing a component failure were encountered:

1. The feed encoder bar shifted from its precise position due to vibration, thereby exceeding a dimensional requirement relative to the sensor bracket. This was simply fixed by modifying the sensor bracket to track the bar. No further failures were encountered.

2. The rotation sensor ring (whose distance is sensed by the Hall effect sensors to yield rotation angle) became unstuck from the rotating head element to which it had been glued. Glue was used because as a retrofit, it was not practical to breach the rotary head itself and mount it internally, nor to drill and tap into the hardened steel that forms the head. The best long term solution is to design the sensor and ring into the rotary drive head itself. A small change to the dimension of the ring, improved surface treatment prior to application, and a better adhesive seemed to solve the problem however, and no further failures were experienced.

3. Although the instrumented rod was only tested for approximately a half hour of drilling in hard rock (not the softer ore) the electronics appear more than capable of surviving the severe shock. A problem however developed with the outer drill rod that carries the instrumented core. The threads that retain the rod cap underwent some deformation that made later reassembly impossible, in fact resulting in the failure of the threads. INCO has currently undertaken the redesign of the drill rod so that testing of the instrumentation can continue.

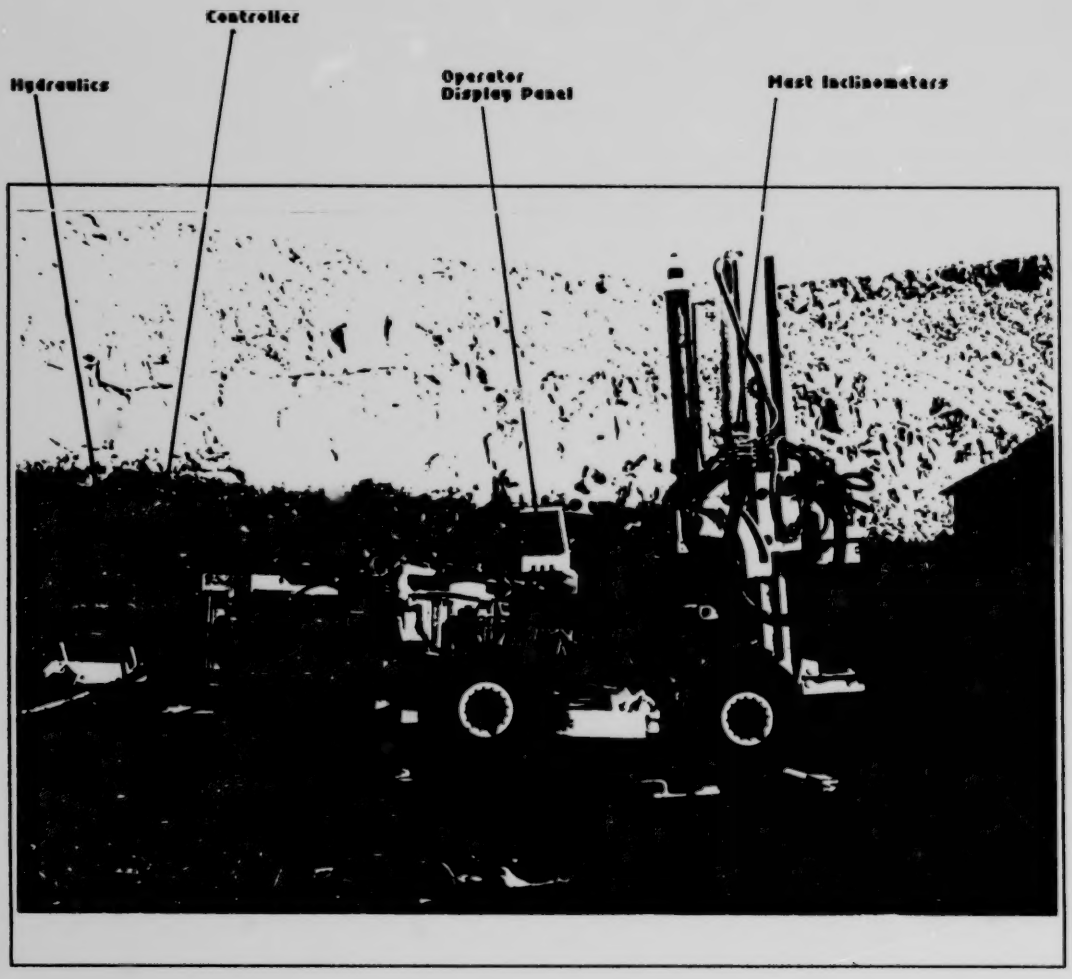


Figure 4.1

CMS CD-90 Drill Rig with VADEKO Instrumentation and Control Accessories

4 Design

4.1 Rig Set-up System

4.1.1 Overview

The purpose of the rig setup subsystem is to enable the operator to position the drill rig and mast with maximum ease and accuracy for a given hole to be drilled. There are two phases to this subsystem: determining the rig's position and orientation; and, determining the required and actual mast angles.

The normal sequence of operation is as follows:

1) the position of the required drill hole is known, along with the dip and bearing desired for this hole. The cross-cut has been surveyed and a number of survey marks, whose position in 3-space are known, are clearly marked on the wall. All this data is available to the controller subsystem, normally transferred from the drawing office to the rig via a bubble memory cartridge. Alternatively, the data can be entered via a keypad on the operator display panel.

2) the rig operator identifies the hole to be drilled and since the position of the holes has normally also been surveyed, can save himself some time by tramming the rig to the vicinity of the hole. Now the computer must determine the rig's position and orientation, basically a problem in surveying. However, since the operator is not a trained surveyor, the following method has been developed:

2a) the operator spots a nearby survey mark and identifies it to the computer. Then he aims the optical setup subsystem at it and presses the trigger button. The optical setup subsystem is basically a type of simple survey instrument. Due to the darkness of the mine, a low-power laser is used to shine a dot of light on the object pointed to, rather than use a telescope or cross-hair sighting device (see figure 4.2). The angle from vertical and the angle of rotation are sensed by angular transducers and read by the computer at the moment the operator presses a trigger button. The operator then repeats the procedure for a second survey mark and then a third.

2b) With this information, the computer calculates the rig's position and indicates to the operator via the display panel the distance of the current rig position from the hole and in what direction the rig must be moved. The operator then moves the rig and repeats the procedure to identify to the computer the rig's new position. If the operator decides the rig is close enough, he then proceeds to the next step.

2c) The display also tells the operator the dip and swing angles to which the mast must be set. Since the rig's orientation is known, as well as that of the required hole, the computer can determine what compound mast swing and dip setup angles are required, IRRESPECTIVE of rig orientation. Therefore the operator does not have to spend time carefully aligning the rig with the required hole bearing so that the hole dip can be set by using only the swing or dip controls, one of the most error prone steps of current practice. The display updates the actual mast dip and swing angles in real time as the operator is changing them, thus speeding up and improving the accuracy of setup. When the operator is satisfied with his setup, he can proceed to drill the hole.

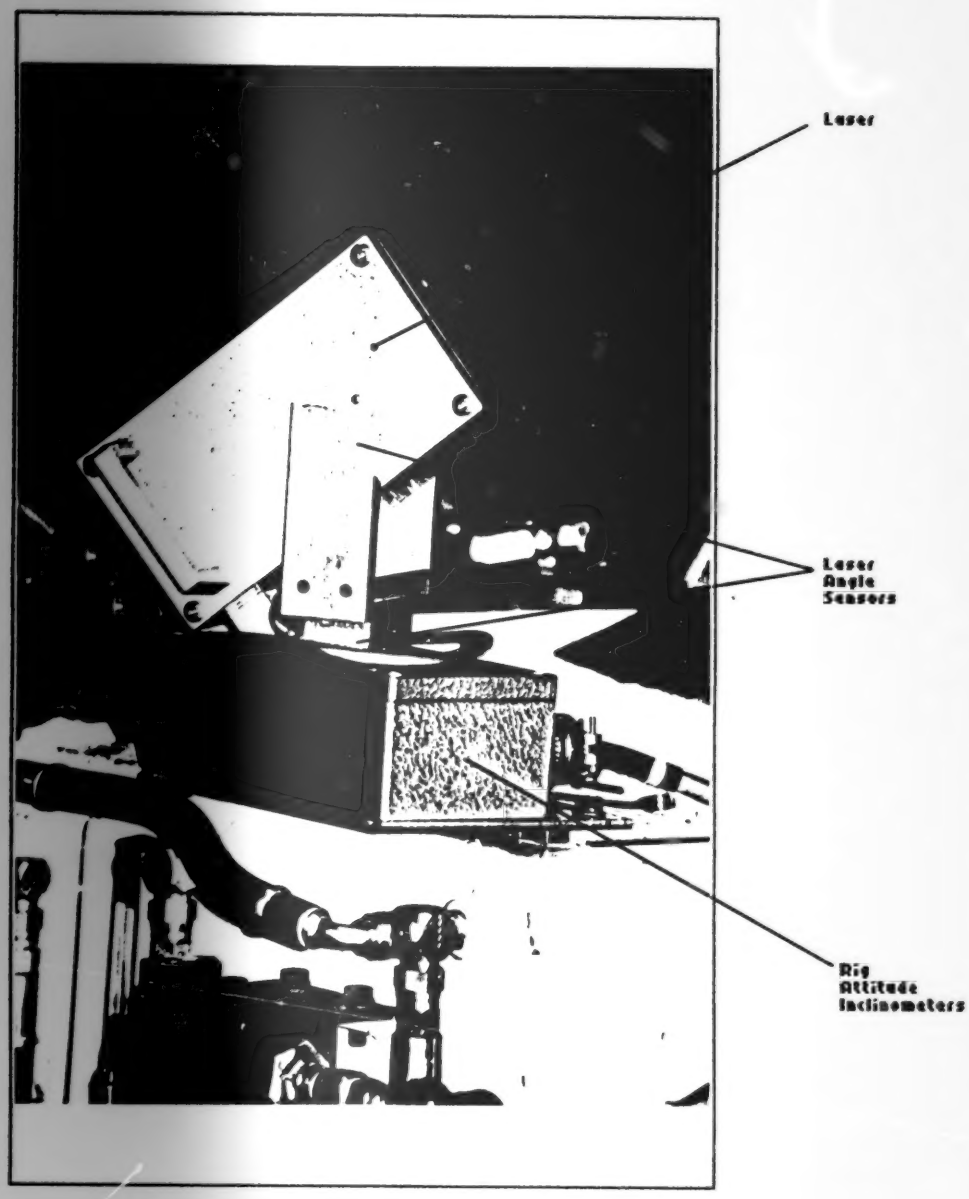


Figure 4.2 a)

Rig Setup Sub-System
Laser and Rig Attitude
Sensors

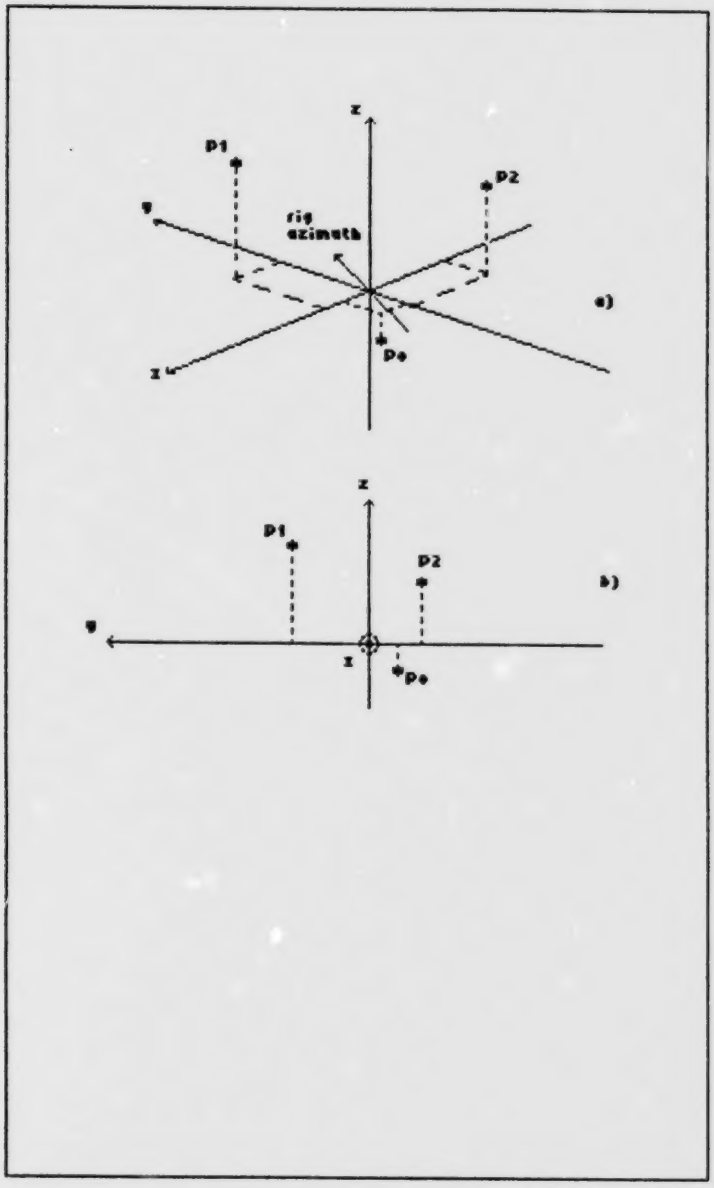


Figure 4.2 b)

Rig Orientation
Test Points P1 & P2

4.1.2 Hardware

The RSS consists of three assemblies: the mast orientation assembly; the rig orientation assembly; and, the optical setup assembly. Both the mast and carrier orientation assemblies consist of a pair of inclinometers, type Sperry Accustar, mounted firmly to the rig mast and main frame respectively. Each pair is mounted at a right angle to each other and setup to sense the "dip" (rotation about x, forward and back), and "swing" (rotation about y, side to side) angles. With the rig on level ground, and the mast exactly upright, all sensors will read zero degrees. It should be noted that the mast angles are absolute, not relative to the rig angles. The rig angles are used to "correct" the data returned from the optical setup assembly. This is required because the algorithm for finding the rig's position and orientation assumes data from a "level" setup.

The optical setup system assembly consists of the laser, mounted in an instrumented gimbal capable of measuring the elevation and heading of the laser assembly (see figure 4.2). The laser provides a narrow beam of light which the operator aims at the survey mark. The bright red spot produced by the laser is clearly visible, even in a lighted area. The laser is a MELLES GRIOT 0.5 mW Helium Neon laser tube, model 05LHR625. It is a rugged device and is further shock mounted within a sealed die-cast metal box. The low power of the beam minimizes any safety hazard to the operators, although intentional prolonged staring into the beam can cause eye damage. The laser is activated by a momentary contact switch, pushed by the operator as the laser is aimed. When the operator releases the assembly, the laser is automatically turned off. This prolongs laser life and maximizes safety.

The laser containment box is mounted on a two axis gimbal. As each axis is rotated, the angle is tracked by two potentiometers

integrated into the assembly. These are high resolution, shock and vibration resistant devices made by PENNY & GILES model HRP15/1S. They provide a voltage from -1Ø VDC to +1ØVDC which is linearly proportional to the angle of the corresponding gimbal axis. These voltages are fed directly to the microcomputer.

4.1.3 Algorithm

The data acquired from the optical setup assembly consists of two values per survey point: vertical elevation and relative heading. The heading (rotation about Z, the vertical axis) is calibrated to be Ø.Ø when the assembly is aimed straight in front of the rig. Values for two survey points yield a relative angle: the horizontal angle between the two survey points with the rig at the vertex. Given this angle and the position in 3-space of the two points it is not possible to solve for the rig's position, as it can lie anywhere along a curve extending from one point to the other. At all points along this curve, lines drawn to the two survey points will form the given angle. For example, if the angle is 9Ø degrees, the curve will be a circle. The only other pieces of information available are the elevation, or vertical angle, of the survey points, relative to the assembly. Standard survey techniques require that either two lengths and an angle, or two angles and a length be known in order to solve for the position of the third point by simple trigonometry. The data available only provides one length and one angle, and it is not acceptable to require the mining operator to obtain the length of a side by normal surveying practices. Therefore, an algorithm has been developed which finds the position to the required accuracy given the two additional vertical elevations.

We start by identifying the following variables:

θ_{cx} : rig swing angle

θ_{cy} : rig dip angle

θ_{1xy} : angle of elevation of 1st survey mark, (not a function of heading).

θ_{1z} : heading angle of 1st survey mark, relative to a "home" position, and not a function of elevation.

θ_{2xy} : angle of elevation of 2nd survey mark.

θ_{2z} : heading angle of 2nd survey mark.

4.1.3.1 Compensation of Rig Attitude

The algorithm assumes the rig is level, so the first step is to correct $\theta_{1,2xy}$ and $\theta_{1,2z}$ by undoing the effect of θ_{cx} and θ_{cy}. This is not simply a matter of rotating by the negative of the angles. It is simpler to transform θ_{cx} and θ_{cy} to a compound rotation angle: θ_{cxy} the angle of inclination of the rig, and θ_{cz} the angle (relative to the front of the rig) of maximum inclination. The transformation is as follows:

$$\theta_{cz} = \tan^{-1}\left(\frac{\tan\theta_{cy}}{\tan\theta_{cx}} \right)$$

and

$$\theta_{cxy} = \tan^{-1}\left(\sin\theta_{cz} \times \tan\theta_{cx} \right)$$

$$= \tan^{-1}(\cos\theta_{cz} \times \tan\theta_{cy})$$

It should be noted that arctangents should be calculated using a full four quadrant algorithm. (see appendix A for full development).

Now to correct $\theta_{1,2xy}$ and $\theta_{1,2z}$, which are taken relative to the rig, it is necessary to mathematically rotate the rig to level by rotating by $-\theta_{cxy}$ about an axis that is perpendicular to the vector of maximum inclination described by θ_{cz}. This can be done by the following three steps:

1) rotate by $-\theta_{cz}$ effectively aligning the inclination with the positive X axis.

2) rotate by $-\theta_{cxy}$ about the X axis, leveling the rig.

3) rotate back by $+\theta_{cz}$ to undo the initial rotation. However, while we are rotating the rig's frame of reference, the vectors described by $\theta_{1,2xy}$ and $\theta_{1,2z}$ remain stationary in the mine's frame of reference. Since all we want is to correct the vectors. we note that a rotation of the rig about the X axis corresponds to an opposite rotation of the vector about the same axis. However, steps 1 and 3, the rotation of the rig to a convenient orientation in order to level the rig, must be applied to the vectors as well. If we represent the vectors described by $\theta_{1,2xy}$ and $\theta_{1,2z}$ by their cartesian components, we get for the i'th vector:

$$Q_i = (\cos\theta_{ixy} \times \sin\theta_{iz} , \cos\theta_{ixy} \times \cos\theta_{iz} , \sin\theta_{ixy})$$

and the algorithm becomes

1) rotate Q_i by $-\theta_{cz}$ degrees about Z axis

2) rotate Q_i by $+\Theta_{cxy}$ degrees about X axis

3) rotate Q_i by $+\Theta_{cz}$ degrees about Z axis

The three rotations can be combined into the single matrix (see appendix A.2) to yield

$$[\ Q_i'\ ] = [\ Q_i\ ] \begin{bmatrix} & & \\ & R_m & \\ & & \end{bmatrix}$$

Finally, we transform Q_i' back to an angle pair Θ_{xy}, Θ_z with

$$\Theta_{ixy}' = \tan^{-1}\left(\frac{Q_{iz}'}{\mathrm{SQRT}(Q_{ix}^2 + Q_{iy}^2)} \right)$$

$$\Theta_{iz}' = \tan^{-1}\left(\frac{-Q_{ix}'}{Q_{iy}'} \right)$$

4.1.3.2 Position Algorithm

Now, given $\Theta_{1,2xy}'$, $\Theta_{1,2z}'$ and the two known survey points $P_{1,2}$, the problem is to find the position of the optical setup assembly, $P_\emptyset$, and thereby the rig. Each Θ_{ixy}' defines a conic surface with vertex at P_i, axis parallel to the Z axis, and a surface slope given by Θ_{ixy}' (see figure 4.3). $P_\emptyset$ can lie at any point on the surface of cone i. Since we have two sets of readings, and hence two cones, there will be a curve which

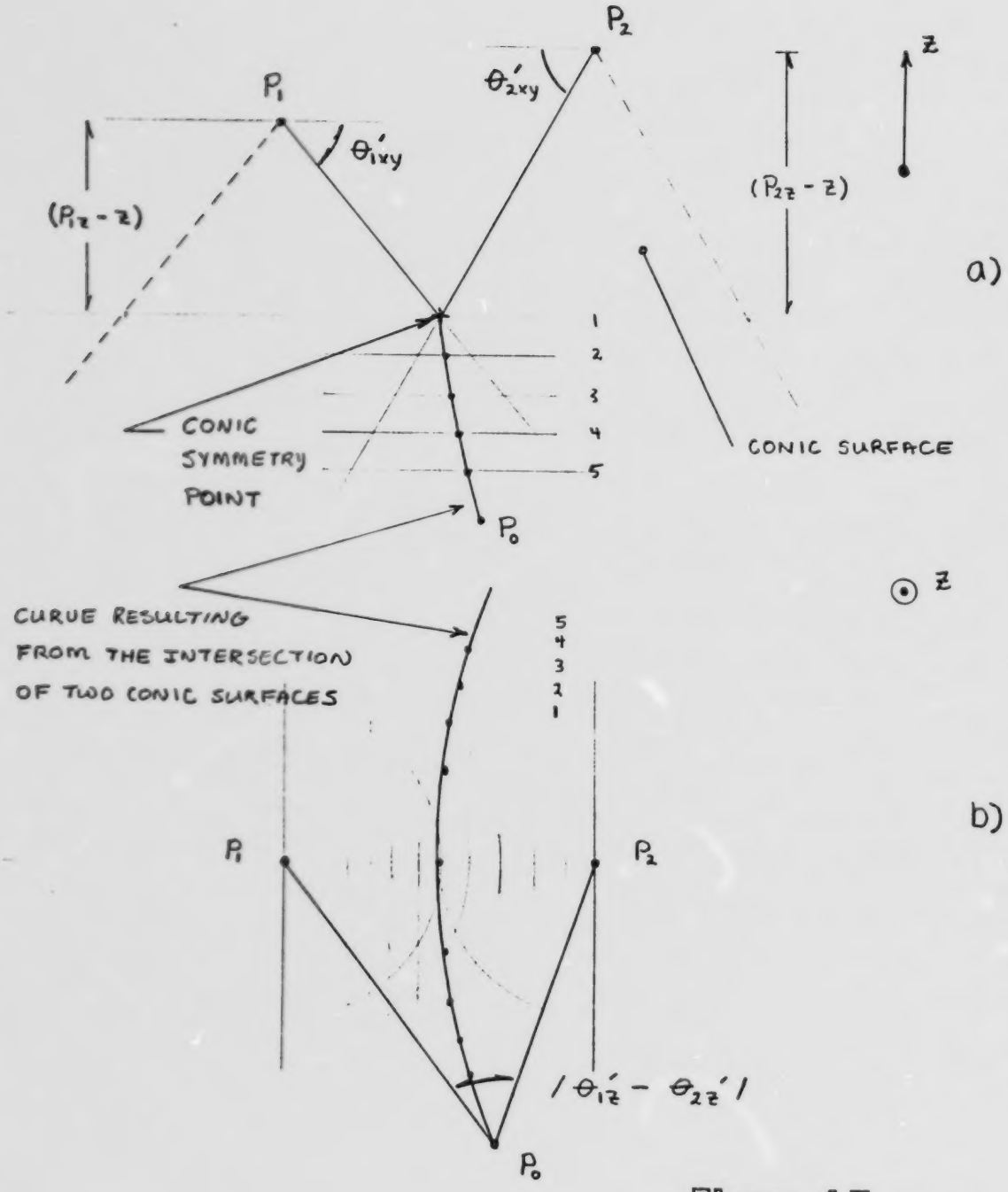


Figure 4.3

Conic Surface Intersection

defines the intersection of the two cones. This curve takes several forms. If either θ_{xy}' is zero, then the cone is in fact a horizontal plane, and the intersection a circle. If both θ_{xy}' are zero, then the algorithm will fail, and another point must be used. If $\theta_{1xy}' = \theta_{2xy}'$, then the intersection curve stretches to infinity, else it always forms a closed curve. The curve is always symmetrical about the vertical plane containing P_1 and P_2. There will in fact be two curves, since the cones exist both above and below the vertex point. The conic half of interest depends on the elevation angle: a positive angle indicates the rig is in the lower cone, and a negative angle indicates the upper cone. This data will eliminate one of the curves, so there is a single intersection curve to deal with.

At each point along the curve, per side, a unique angle is formed between the vectors extending to the two points. At the point on the curve equal to the desired position, that angle will be equal to the observed difference angle $|\theta_1' - \theta_2'|$. The algorithm to find the position is iterative: given a starting point on the curve (on the plane of symmetry), a test point travels along the curve until the required angle is formed.

4.1.3.2.1 Initial Conditions

The starting point is always the point of symmetry, or inflection, of the intersection curve, and is on the vertical plane containing the two survey points. The Z value of this point is (see appendix A.3):

$$P_{sz} = P_{2z} - \left(\frac{L_{xy}\sin\theta_1\sin\theta_2 + (P_{2z}-P_{1z})\cos\theta_1\sin\theta_2}{\sin(\theta_1 + \theta_2)} \right)$$

where $L_{xy} = SQRT\ ((P_{2x}-P_{1x})^2 + (P_{2y}-P_{1y})^2)$

4.1.3.2.2 Test Point Coordinates Function

For a given value of Z, it is possible to calculate the points at which the cones intersect. The problem becomes simply one of calculating the intersection of two circles, centered at (P_{1x},P_{1y}) and (P_{2x},P_{2y}) respectively, with radius

$$R_1 = (P_{1z} - Z) \times \tan(90 - \theta_{1xy})$$

and $$R_2 = (P_{2z} - Z) \times \tan(90 - \theta_{2xy})$$ respectively.

Given L_{xy}, the distance on the XY plane between the points, we may determine whether the circles intersect at 2 points, 1 point, or not at all, as follows:

$R_1 + R_2 = L_{xy}$	1 point
$R_1 + R_2 < L_{xy}$	no intersection
$R_1 - R_2 > L_{xy}$	no intersection
$R_2 - R_1 > L_{xy}$	no intersection
$R_1 + R_2 > L_{xy}$	2 points (given above conditions false)

If the circles do intersect we can calculate half of the angle subtended at P_1 by the two points of intersection (see figure 4.4). using the cosine law as follows:

$$\phi = \cos^{-1}\left(\frac{L_{xy}^2 + R_1^2 - R_2^2}{2 \times R_1 \times L_{xy}}\right)$$

If we calculate the angle of L_{xy} relative to the X axis as

$$\beta = \tan^{-1}\left(\frac{P_{2y} - P_{1y}}{P_{2x} - P_{1x}}\right)$$

then the intersections lie at a distance of R_1 from P_1 and at an angle of rotation of $\beta+\phi$ and $\beta-\phi$. The two new points P_a and P_b can be found with

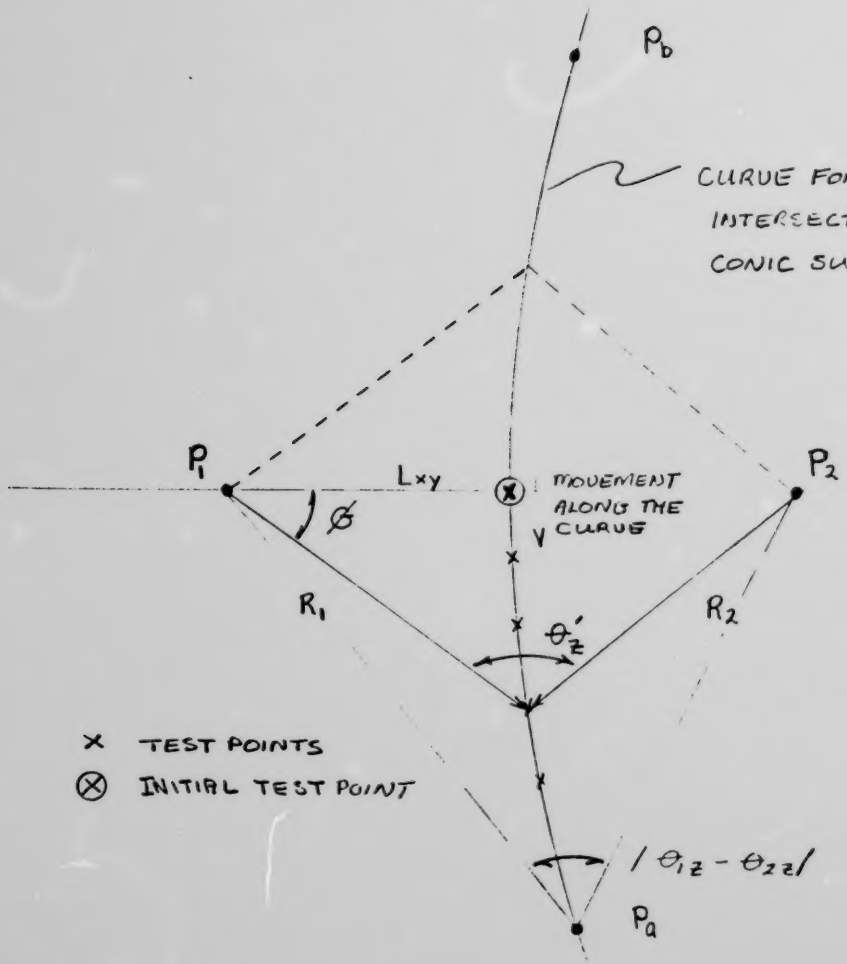
$$P_{ax} = P_{1x} + R_1 \times \cos(\beta + \phi)$$
$$P_{ay} = P_{1y} + R_1 \times \sin(\beta + \phi)$$

$$P_{bx} = P_{1x} + R_1 \times \cos(\beta - \phi)$$
$$P_{by} = P_{1y} + R_1 \times \sin(\beta - \phi)$$

4.1.3.2.3 Subtended Angle Function

Now that P_a and P_b are specified (for a given Z), it remains to determine the relative heading angle subtended by P_a (P_b is symmetrical) and the two survey points:

$$\cos(\theta_z') = \left(\frac{R_1^2 + R_2^2 - L_{xy}^2}{2 \times R_1 \times R_2}\right)$$



NOTE: P_a AND P_b REPRESENT THE TWO POSSIBLE RIG LOCATIONS FOUND BY THE ITERATIVE ALGORITHM

Figure 4.4

Relative Heading -Iterative Approach

This angle, resulting from the estimated Z, is compared to the required angle $|\theta_{1z} - \theta_{2z}|$. For higher efficiency, the algorithm actually compares the cosine of the angle. If the error is too large, then P_a and P_b must be moved along the intersection curve. As described above, this is actually done by changing Z and calculating the resulting XY coordinates.

4.1.3.2.4 Iterative Algorithm

The step size and direction are initialized to values that guarantee a valid point is found. If after incrementing Z, no intersection can be found, then it is necessary to return one step back and proceed with smaller steps. The rate of change of the error in the resulting $\cos\theta_z - \cos\theta_z'$ is also monitored. If the error begins to increase, then this is an indication the point has been missed, and the direction of increment must be reversed and the step size reduced. This iterative procedure is repeated until the change in $P_{a,b}$ from one step to the next is less than some required positioning accuracy. Provided the data is valid, a solution must exist. If one does not, or if the remaining error in the angle is too great, then this is an indication the measurements are not valid, i.e., the operator was not aiming at the survey marks with sufficient accuracy. By starting the algorithm at the point of inflection of the curve, the point of minimum error will always be found. The algorithm finds the rig's position surprisingly quickly, so no attempt has been made at this time to optimize the step size to reduce the number of iterations.

4.1.3.3 Final Calculations

Since the algorithm generates two possible points from two survey marks and one set of inputs (see figure 4.4), it is necessary to resolve the ambiguity by using a third mark. Applying the algorithm to the second and third marks and inputs results in two more points, one of which should coincide with one of the first two points. For added redundancy, the first and third marks could also be used to generate yet another pair of points. There will be a unique set of three points (one from each pair resulting from application of the algorithm) which has the minimum deviation. The mean of the three points can be used as the rig's actual position, and the deviation (root mean square) of the three points as a measure of the accuracy with which the laser was aimed.

Once the center of the optical setup assembly has been determined it is a simple matter of geometry to calculate the position of the drill point itself and the orientation of the rig.

4.1.3.4 Required Mast Angles

With the rig's orientation determined, and if the desired drill hole is defined, then the required compound mast angles can be calculated and displayed to the operator. The problem is to align the drill vector, described in absolute dip and azimuth angles Θ_{dp} and Θ_{az}, with the mast of the rig, described in terms of erection and swing Θ_{er} and Θ_{sw}.

The absolute azimuth of the rig itself, known as a result of the procedure described in the above sections, must be taken into account. This is done by introducing the relative azimuth of the hole (relative to the rig) defined as

$$\Theta'_{az} = \Theta_{az} - \Theta_{rig\ az}$$

The full development of the mast calculations are found in appendix A.4. The compound angles are calculated as

$$\theta_{sw} = \sin^{-1}(\sin(\theta_{dp}) \times \sin(\theta'_{az}))$$

$$\theta_{er} = \tan^{-1}(\tan(\theta_{dp}) \times \cos(\theta'_{az}))$$

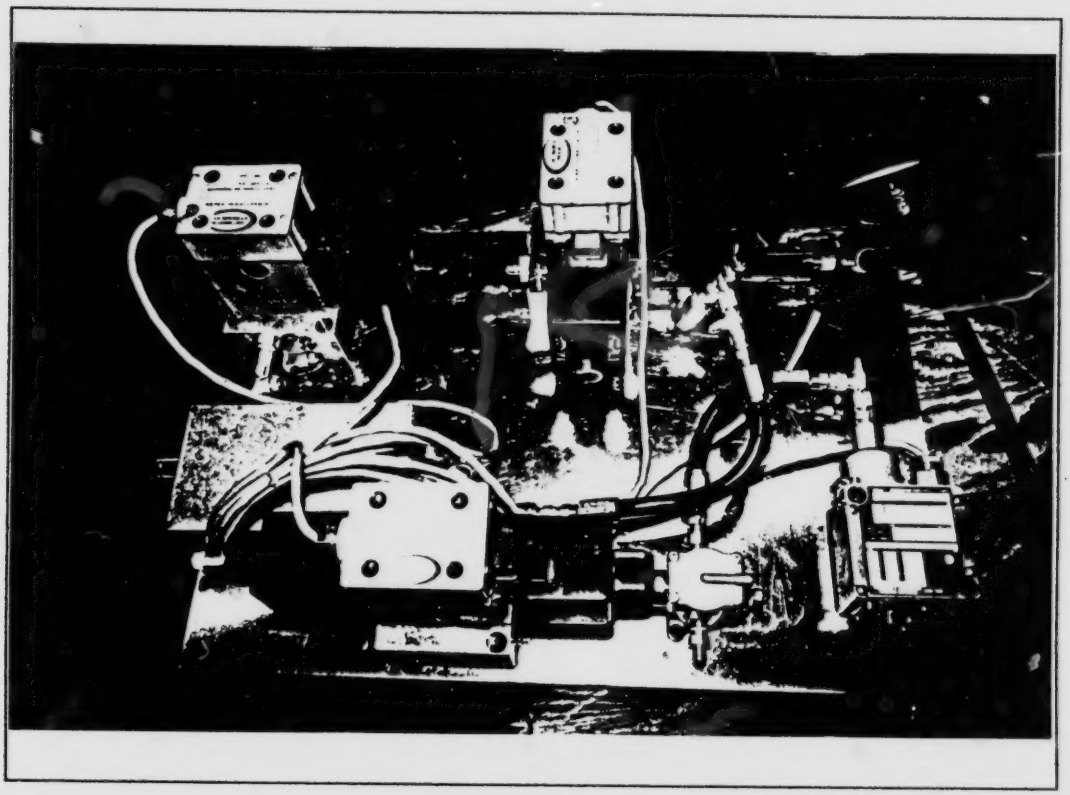
4.1.4 Summary

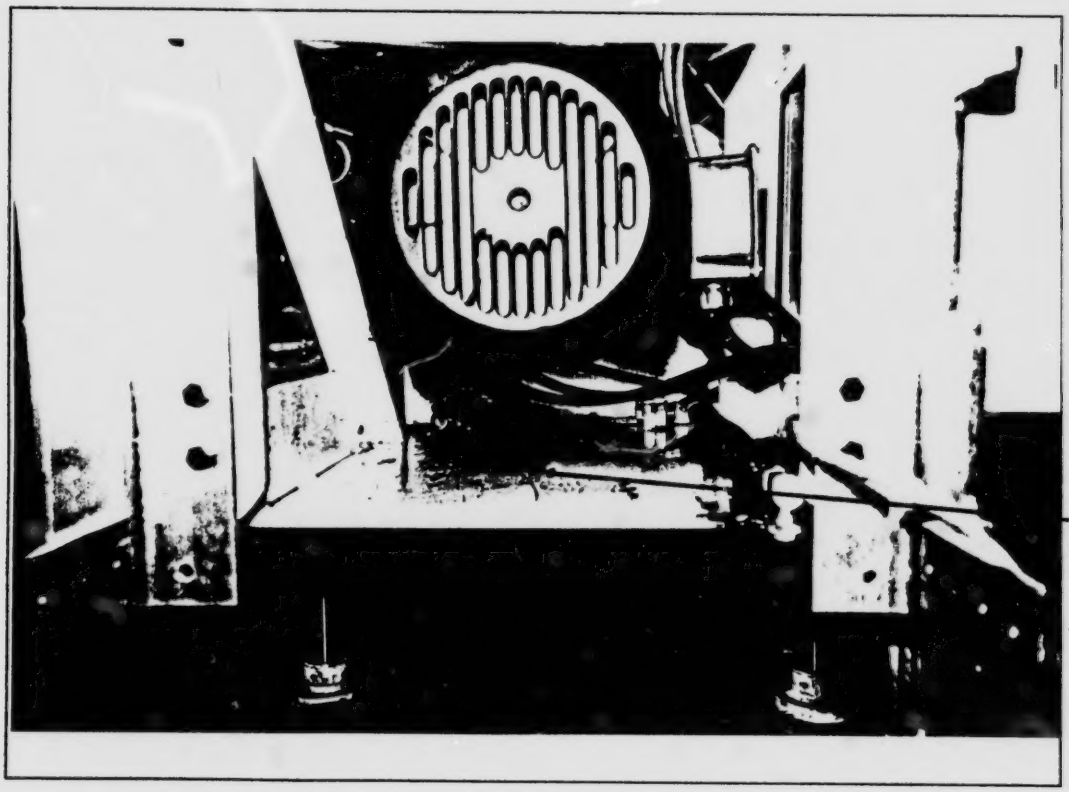
The algorithm has been verified by using a simulation. Given a set of three actual survey mark coordinates, and a test position and orientation of the rig, the angles that the operator would input by aiming the laser at the three marks are calculated, assuming zero error. Then using these angles as inputs, the algorithm is used to calculate the rig's position. Provided the marks were reasonably well distributed and within about 50 feet, the algorithm was able to determine the rig's position and orientation to less than one hundreth of a foot in about 4 seconds. In practice, errors in the calibration of the laser orientation sensors, and in the aiming process introduces errors which increase the deviation. The maximum acceptable deviation reflects the accuracy required.

At present, the rig's collaring position and orientation is displayed to the operator for direct comparison to those specified on the surveyor's plans. If the drill hole location has been entered (manually or via bubble memory) then a more user friendly software could be added to convey direction and required distance to move the rig.

When the operator is setting up the mast and hole data is known, and the laser system has been used, then the required mast angles are displayed as well as the actual angles, along with graphic arrows clearly indicating which way to adjust the mast erection and side swing. It should be noted that the mast setup angles can always be displayed, regardless of whether or not hole data or rig position data is available.

Figure 4.5: Drill Hydraulic Sub-System





4.2 Drill Hydraulics Subsystem

4.2.1 Overview

The Drill Hydraulic Subsystem (DHS) (see figure 4.5) comprises the set of actuators and sensors which allow the controller subsystem to monitor and control the drill parameters. The desired end result is to minimize drill costs. The cost of drilling is a function of time (drill rate), of consumables such as the drill bits, and of wear on the drill string, hammer, and rig, causing reduced performance and eventually downtime. Simply maximizing the drill rate may cause excess wear and eventual failures which will increase cost.

Presently, the rig operator controls two parameters while drilling: the weight on bit (WOB) and the speed of rotation of the drill pipe and bit. For a given speed at which the bits hit the rock, the drill rotation adds a sideways component, resulting in the bit hitting the rock at an "index angle". Hence, drill pipe rotation is often referred to as indexing. The amount of rock chipped away or crushed by the bit is a function of this bit index angle, blow energy, and the rock type, all of which affect the drill rate. For a given hammer and rock type, the drill rate is therefore a function of the weight on bit and the indexing rate.

VADEKO's drill automation system attacks the cost of the drilling process itself in three levels:

1) Under computer control, WOB and indexing rate are set and maintained by the computer, which automatically compensates for changes in the rock, drill string weight, binding, etc. Smooth, constant control reduces shocks, cycling and improper setting of the rig's hydraulic systems, thus minimizing wear. Dangerous

conditions, such as binding of the drill string can be detected and action taken before damage is done.

2) An optional adaptive control loop monitors feed rate and modifies the WOB and indexing rate settings so as to maximize feed rate. Maximum and minimum limits are used to protect the equipment from excessive settings.

3) The settings and the resulting feed rate are monitored and logged for later analysis to help determine the optimum settings and limits.

4.2.2 Sensors

Although some sensors are applicable to many different makes of rigs, some will always require redesign for integration into a different rig. Those sensors requiring a design specifically for the CD-90 were designed to be as universal as possible, so that a minimum of changes would be required to adapt the design to a different rig.

The sensors required by the DHS are as follows:

1) Feed position/rate: the drilling rate is the rate at which the drill pipe is advanced into the rock. It is possible to derive this from the feed position (position of the rotary head on the mast). This is preferrable due to the range of rates (close to zero while drilling) and also to enable automated positioning of the drill pipe for pipe addition/removal.

2) Indexing position and rate: for the DHS, only the indexing rate is required. However, the Instrumented Rod Subsystem requires that the absolute rotation angle of the drill pipe be known in order to accurately calculate the position of the drill

bit.

3) Weight on bit (WOB): this is the sum of the weight of the drill string and the weight exerted by the drill rig on the drill string. This "feed pressure" is the actual parameter set and controlled, and will be negative ("holdback force") when the weight of the string exceeds the WOB.

4) Drill air on: an air pressure switch is used to ensure that drilling air has been turned on, either manually or automatically, before the drill bit contacts the rock.

5) Automation interlocks: this group of sensors is used to ensure the operator has set various valves in a position that is safe and compatible with the automated control loop.

Feed Position

The feed position sensor provides information about the position of the rotating head on the mast. It must be very rugged to withstand the vibration and dirt experienced by this area of the rig, as well as the possibility of being hit by pipes, wrenches, etc. The sensor must work over a linear range of 6 feet. On the CD-90, the head is actuated directly by a hydraulic cylinder with no rotating elements. Rather than add a possibly unreliable mechanism to a rotary transducer, direct linear position sensing was chosen. It is believed this approach will also simplify redesign for other types of rigs. Resolution of the sensor does not need to be very fine; a value of .250 inch was chosen as it provides a good compromise between increasing resolution on the one hand, and reliability and cost on the other.

The transducer is basically an incremental encoder, generating a

string of "up" and "down" pulses as the head moves up and down the mast. The pulses are counted by the microcomputer which takes the difference of the two to determine the actual feed position. Rate of change of feed position is then calculated to yield feed rate. As is required with any incremental encoder, proximity switches at the top and bottom extreme of the mast travel detect the limit conditions, and are used by the computer to initialize the pulse count when the machine is initially turned on, as well as provide a check every time the head reaches its upper or lower limit.

The transducer itself consists of the following component assemblies:

1) a linear vane, extending the full 6 feet, is bolted securely to the mast structure. It is made from steel and sufficiently rugged to withstand impacts. One-half inch holes are cut along its length, spaced 1 inch apart. It is the presence or absence of metal in this vane that is sensed as the head moves.

2) two proximity sensors are mounted on the head and are moved along the vane as the head moves, detecting the presence or absence of metal. The two sensors are spaced 3/4 inch apart, or 90 degrees out of phase. This makes it possible to determine whether the movement is up or down, as well as increase the resolution to 1/4 the period of the vane, or 1/4 inch.

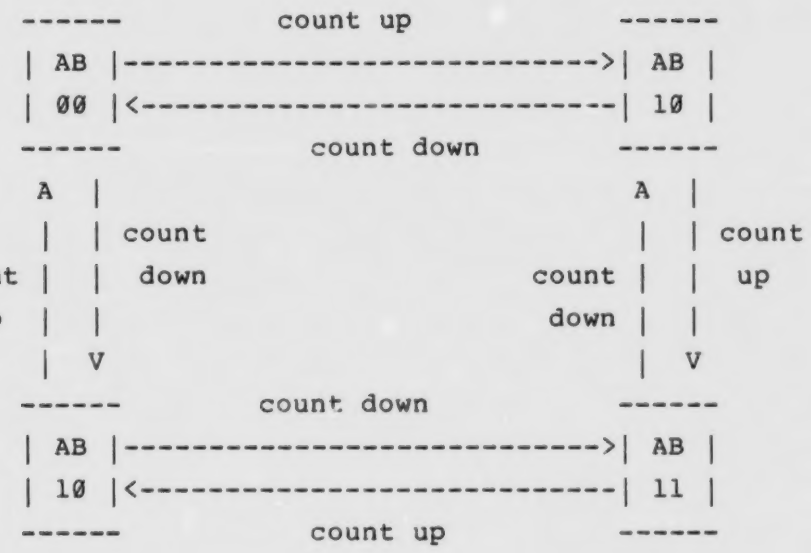
3) logic circuits located in the controller subsystem receive the two proximity sensor signals and generate the appropriate "up" and "down" count pulses to be processed by the microcomputer.

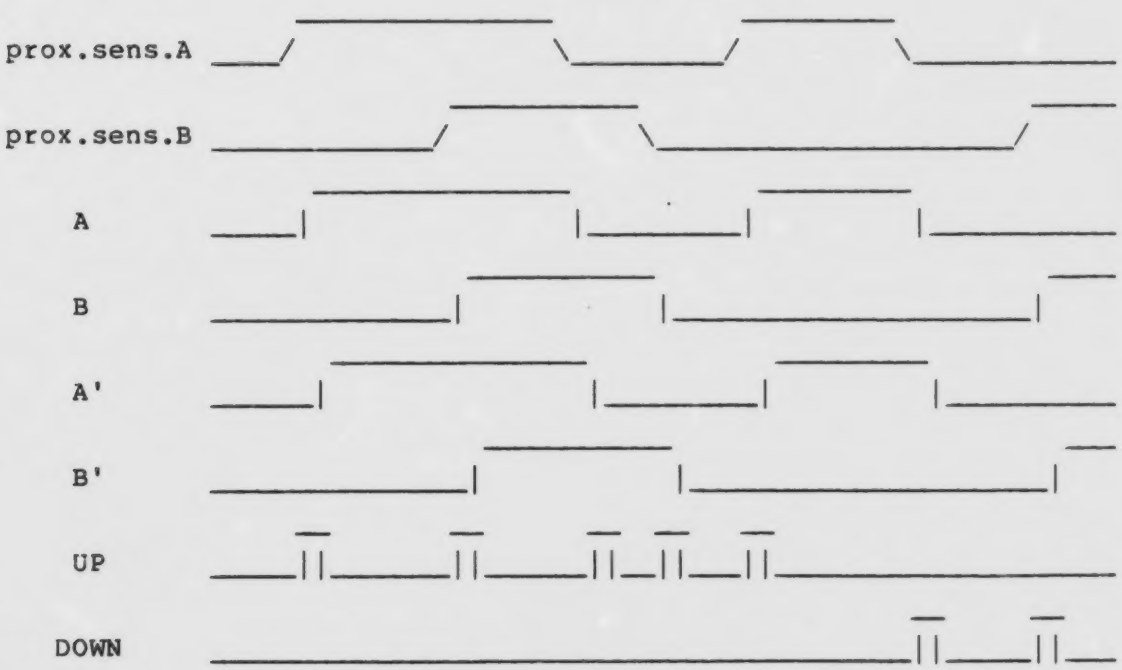
The proximity sensors are standard sealed, inductive devices, mounted in a housing which rides along the vane. They require 24 VDC and ground, and present an "NPN open-collector" type output. This means the outputs behave like a switch connected to the ground that is closed when the metal is present and open when

absent.

The logic circuits are found on the auxiliary interfaceboard (AIB) of the controller subsystem. The sensor ouputs are "pulled up" by a resistor to generate a valid logic level for the circuits. In addition, an RC network provides some filtering (approx. time constant = 50ms) to suppress interference noise and possible instability. The signals are buffered by Schmitt triggered devices and then fed to two pairs of clocked latches. A 10 Hz clock samples each of the two signals, generating what we will refer to as signals A and B. These signals will therefore only change once per clock pulse. They are fed to a second set of latches, similarly clocked, to generate A' and B' which are delayed from A and B by exactly one clock pulse and form the "previous state" of A and B. A combinatorial logic circuit combines the present and previous sensor states to yield an "up" or "down" pulse whenever there is a change in the sensor output, i.e., at every transition. The following diagram illustrates the function of the logic circuit and a sample timing of the signals:

Figure 4.6: Feed Position Sensor





The logic circuit has been implemented in CMOS for greater noise immunity and lower power consumption. When a vane edge is crossed very slowly, such as while drilling in hard rock, the up and down vibration of the sensor may exceed the hysterisis of the proximity sensor, resulting in an unstable output. If this problem is not taken into account, the wrong count and hence position would result. Several steps have been taken to eliminate this problem. First, the signal transitions are filtered by an analogue RC filter and then by the digital sampling frequency. Secondly, the 90 degree phase shift of the sensors causes only one output to change at a time. This "grey code" ensures that if a single sensor signal oscillates, it will generate an equal number of up and down pulses. Therefore when the computer takes the difference in the number of pulse counts, it automatically cancels out errors due to this instability. The computer's algorithm also checks for overflow and other possible error conditions.

Indexing Position and Rate:

The indexing sensor must operate reliably in one of the most rugged areas of the rig. The absolute rotation angle must be known to within approximately 1.5 degrees (as required by the IRS). Although this would initially appear to be a simple matter of attaching a rotary absolute encoder to the rotary head, this would be complex to design and difficult to retrofit in the CD-90. The simplest place to gain access to the rotating elements is at the bottom of the head, where the drill pipe engages the floating head. Here a cover ring plate protects the oil seal between the stationary and rotating components. The ring can be easily replaced by another ring containing the transducer and extending a further 1/2 inch. The small space and rugged environment eliminates the use of mechanisms with moving parts or

any known commercial sensor.

The indexing rotation position sensor consists of an eccentrically mounted ring that rotates with the head, thereby appearing to move towards and away from two HALL-effect sensors positioned 90 degrees apart on a stationary outer ring. The HALL sensors generate an output signal that is directly proportional to the intensity of the magnetic field (GAUSS) through the sensor, and is therefore totally unaffected by contamination and vibration. A magnet is fixed .125 inch behind each of the sensors to provide a constant field through and in front of the sensor. When a ferrous object is brought within the field, it disturbs it, thereby varying the output of the sensor. Unlike inductive sensors, the HALL-effect sensor is sensitive to the absolute field intensity, so it is the object's presence, not movement, that is sensed. The ferrous ring is mounted with its center .050 inches off the center of head rotation. The sensor position is adjusted so that the ring comes within .100 inches at its closest point, and is therefore .200 inches away at 180 degrees. The use of two sensors 90 degrees apart resolves the ambiguity of which way the head is turning and provides greater accuracy. There are effectively no moving parts. The ring is only 3/8 inch thick and the HALL sensor and magnet are sealed in a replaceable 1/2 inch thick assembly which mounts directly in a new cover plate, fully protected from the outside.

The HALL-effect sensor outputs change by approximately 200mv over the .100 inch change in ring distance, with a minimum sensitivity of .800 volts per inch at its furthest point. Combined with the microcomputer's analogue input resolution of 625 uv, this yields a sensitivity of .0005 inch. The relationship between the angle of rotation and distance is as follows:

i) treating the outer edge of the ring as a circle of radius R, centered at (B,0) relative to the center of rotation of the head, we get:

$$(X-B)^2 + Y^2 = R^2$$

ii) since we want to get the distance from the center of rotation to the edge of the ring as the angle changes, we convert to the polar coordinate system (L,Θ) by substituting:

$$X = L \times \cos \Theta \quad ; \quad Y = L \times \sin \Theta$$

yielding

$$(L \times \cos \Theta - B)^2 + L^2 \times \sin^2 \Theta = R^2$$

iii) solving for Θ gives the result:

$$\Theta = \cos^{-1} \left(\frac{L^2 + B^2 + R^2}{2 \times L \times B} \right)$$

where B is .005 inch
R is 4.45 inch
and $L = 4.6 - D_H$ the distance of the ring from the sensor subtracted from the sensor from the center point of rotation.

The distance of the ring from the sensor, D_H, is proportional to the output of the HALL-effect sensor, and can be calculated to within a few percent error by

$$D_H = .757 \times V_H^{-4.69}$$

Normally however, a 256 element look-up table is used to quickly map from V_H directly to Θ. First order interpolation between table elements yields sufficient accuracy.

The sensitivity of changes in Θ will be at a minimum when the ring is at its closest or furthest points, and at its maximum when in between. Given the minimum sensor resolution discussed above of .0005 inch, the sensitivity of Θ varies from .57 degree at +/- 90 degrees to 8.0 degrees at 0,180 degrees. Since the microcomputer can select which sensor to use for its calculations, the worst case resolution is approximately 0.66 degrees. In addition, the microcomputer can also compensate for any output variations due to temperature or variation in the magnet over time by taking the maximum and minimum sensor output values over a cycle and calculating new offset and gain parameters for each sensor signal.

Weight on Bit

The weight on the bit is controlled by the "feed pressure" in the hydraulic actuator that pushes the head and drill pipe downwards. This feed pressure is monitored by a pressure transducer type Schaevitz P2593-0001 with a pressure range of 0-2000 psi. The strain gage signals are amplified to give a full range output of 0-5 VDC, and fed directly to the microcomputer's analogue input.

On the CD-90 the feed pressure is applied against a "counter-balance" valve which effectively applies a back-pressure of 800 psi or 4000 lbs. This corresponds to the weight of 40 pipes, so that when the normal maximum depth (40 pipes = 200 ft.) is reached, the weight on bit is equal to the weight applied by the feed pressure, normally 2000 lbs. For fewer pipes, to maintain the same weight on bit, the pressure must be correspondingly more, i.e., 17 psi per 85 lb drill pipe.

Drill Air On

This sensor is a simple air pressure switch which closes at about 40 psi and above. It detects that the high pressure air required to run the drill hammer has been turned on before the hammer is pushed against the rock. Drill air will vary from pressurized mine air at about 100 psi used for hole cleaning, to 250 psi boosted air pressure normally used for drilling. The microcomputer will not apply feed pressure (if in automated mode) unless drill air is available.

Automation Interlocks

These interlocks are very dependent on the particular rig that is retrofitted, both in form and function. Their purpose is to ensure that auxiliary hydraulic systems which will cause a safety hazard are not engaged, and that manual valves that could interfere with the automatic control loops are not on. On the CD-90, the following interlocks have been implemented:

1) TRAM/DRILL: this valve selects whether one of the hydraulic circuits causes the left wheels to rotate, or the drill head to rotate. Since the head rotation is an automated output, it is a safety requirement that this valve NOT be in the TRAM position when the circuit is activated.

2) FEED/DRILL: this valve selects whether or not pressure regulation is applied to the feed actuator circuit in manual mode. In order to control the feed pressure automatically, the operator must not place this valve in the DRILL position before entering the automated drilling mode.

3) manual FEED valve: this manual control valve must be closed before entering the automated drilling mode, otherwise the computer will be unable to regulate the feed pressure.

3) manual INDEX ROTATION valve: this manual control valve must be closed before entering the automated drilling mode, otherwise the computer will be unable to regulate the indexing rate.

4.2.3 Actuators

The DHS can be installed on any of the rigs specified in the project overview in parallel to the existing manual control valves. The components have been selected to accomodate the range of pressure and flow of any of the rigs. The hydraulic circuit will be identical for all systems except for changes to fittings and other items which are necessary to integrate the package into each system. The following areas have been identified as areas that could require modification for each system:

Hardware mounting:
- -hydraulic component mounting interfaces
- -tranducer mountings
- -manual valve proximity detection mounting
- -air solonoid valve and mounting

Integration into existing system hydraulic line
Feedrate feedback device and mounting
Control of pipe clamp and breakout (if necessary)

The DHS integration philosophy is as follows: The hydraulic components are to be installed in parallel with the manual control valves to permit a selection of either automated or manual operation. Feedback devices have been incorporated to determine which mode of operation the system is in, and hydraulic valves have been added to allow switching between man./auto. modes upon instruction at the operator display. The system will not automatically switch between modes if the manual hydraulic

directional valve is in a flow condition - - verified through feedback. If the manual valve is at anytime switched to an open flow condition during operation, the system will instruct the operator to switch it back, or the operation will be terminated. A beeper is used to alert the operator. If electrical power is lost, the DHS components will return operation to the manual mode.

Since the DHS hydraulic components perform functions identical to those now manually operated, additional components for heat generation, relief, etc. will not be incorporated, since they should have been included by the manufacturer if they are necessary. Filtration will be increased to a level compatible with the new valve requirements.

The following figures illustrate the basic functional flow schematics.

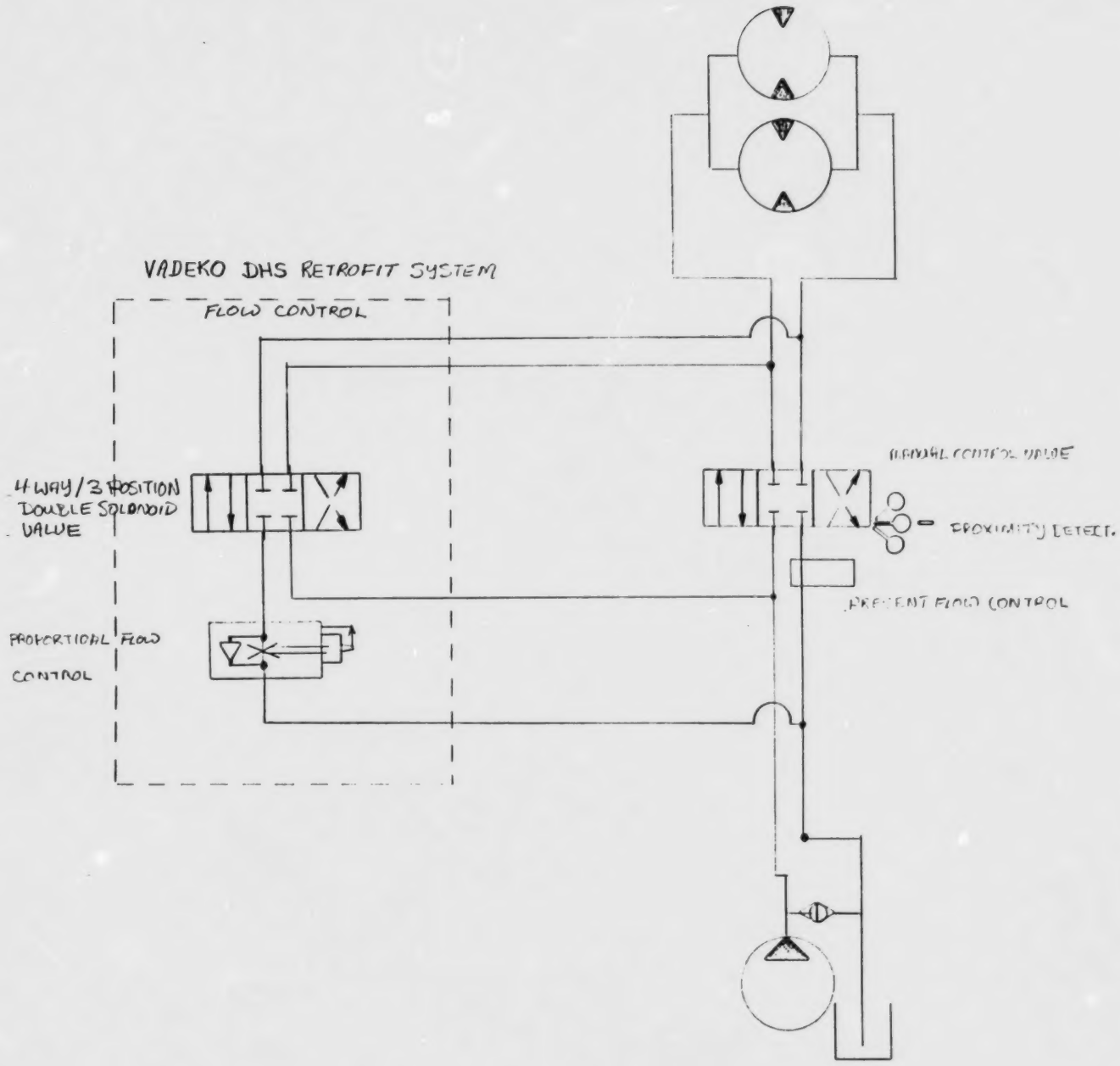


FIGURE 4.7

ROTATION FLOW CONTROL
HYDRAULIC CIRCUIT

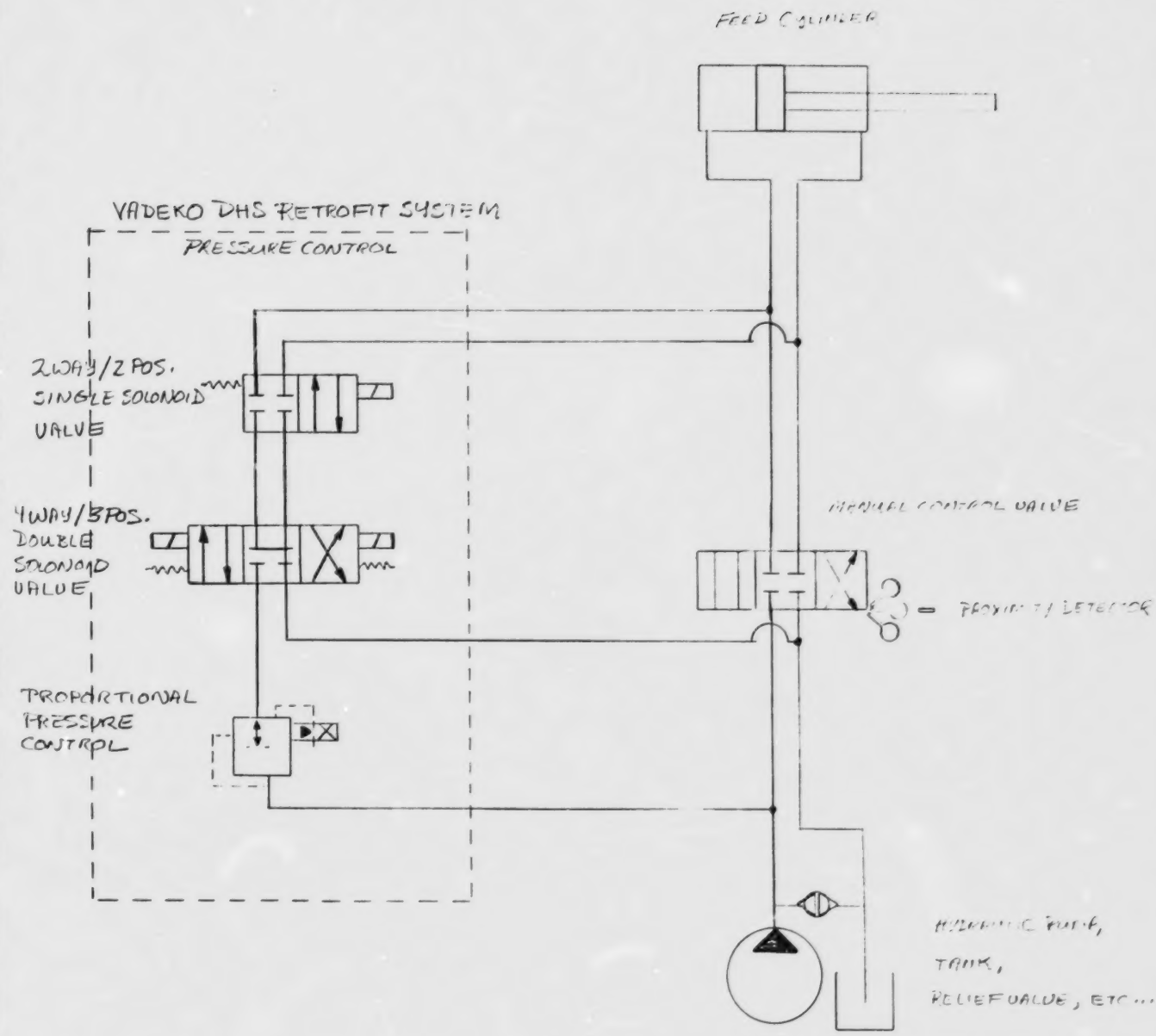


FIGURE 4.8

FEED FORCE HYDRAULIC
CIRCUIT

4.2.4 Software

The software running on the controller must process the raw sensor signals as required and close the two control loops to effect servo control. In addition, the software also determines the required pressure to produce the desired weight on bit (given the weight of the drill string), and sequence through the steps required for automatic control.

4.2.4.1 Adaptive Feed and Rotation Rate Calculation

Both the feed position and rotation angle sensor data must be converted into actual units. In addition, it must be differentiated to yield feed and rotation rate, in feet per minute and rotations per minute respectively. Since in operation the rates will vary greatly (for example, the feed rate varies from over 60 FPM as the operator retracts the head after breakout to under .01 FPM during drilling), the differentiating algorithm uses a variable timebase which it adapts to the characteristics of the incoming data.

4.2.4.2 Calculation of Required Feed Pressure

The calculations required to determine the required feed pressure are as follows:

required_feed_pressure = feed_weight /rig_parms.feed_lbs_per_psi

where:

feed_weight = WOB - head_weight - string_weight + counter_weight

and:

WOB is the required resultant weight on bit in lbs.
head_weight is a rig constant, for the CD-90 = 600 lbs.

string_ weight = number_of_pipes * weight_of_pipe

number_of_pipes is a variable maintained by the system
weight_of_pipe is a rig constant, for the CD-90 = 85 lbs.

counter_weight = counterbalance_force * feed_lbs_pre_psi

counterbalance_force is a rig constant, for the CD-90 = 800 psi.

feed_lbs_per_psi is a rig constant, simply a function of the feed cylinder dimensions, for the CD-90 = 5.

4.2.4.3 Automated Drilling

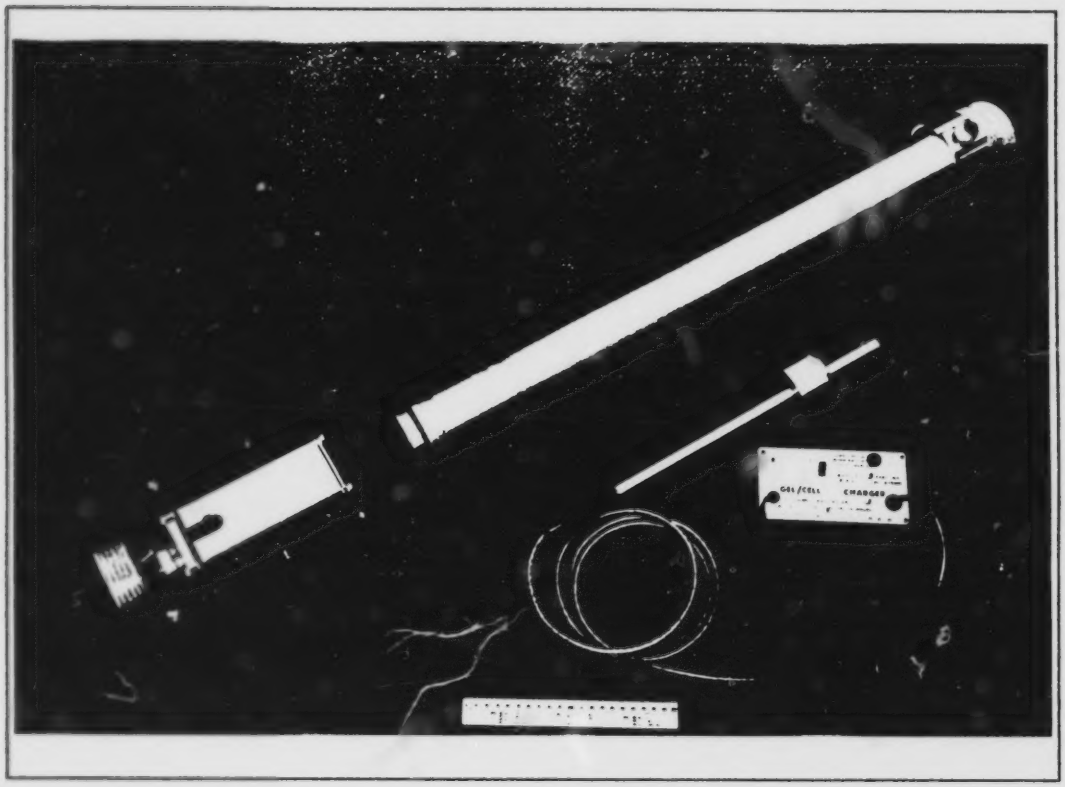
The main software component in controlling the rig parameters is the software servo loop. There are four servos controlling feed position, feed rate, feed pressure, and rotation rate. The latter two are the ones actually used while drilling, while the first two are only used for brief initial and terminal steps of the automatic drilling algorithm.

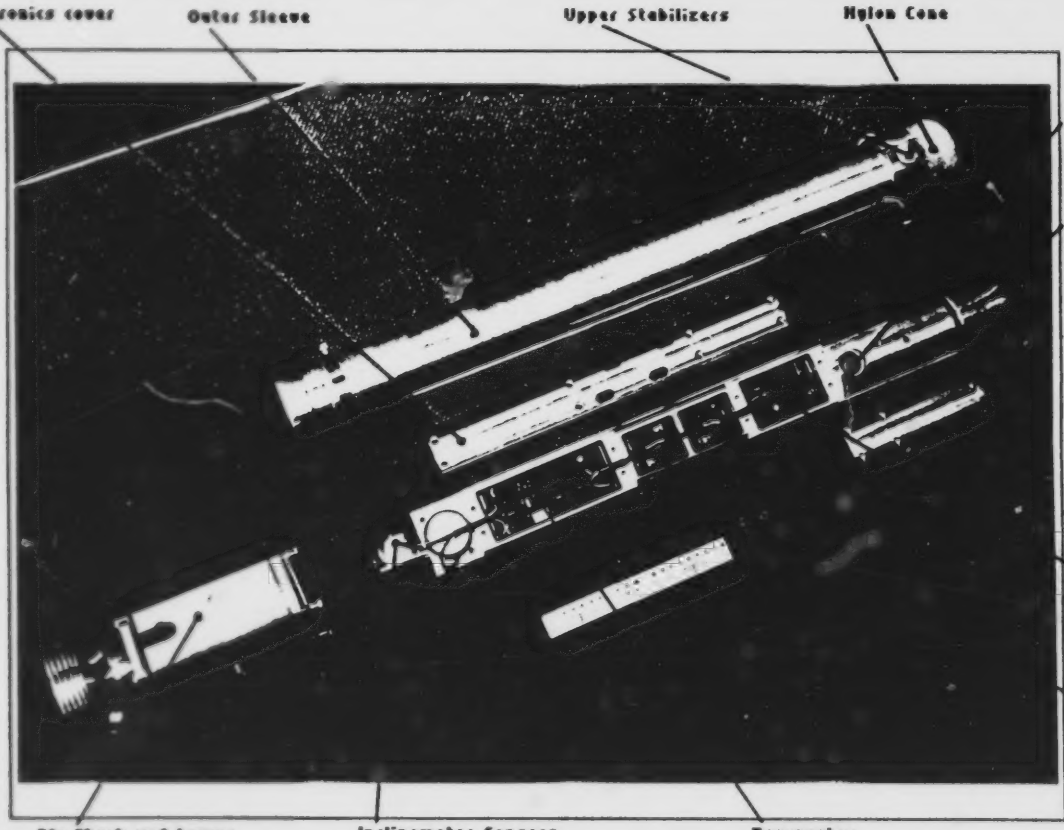
The code used to effect servo control is basically the same in all cases, a simple proportional-integral-derivative algorithm. The parameters for each servo are stored as constants, but can be easily modified.

4.2.5 Summary

The sensors have proven to be very reliable, as have the hydraulic valves. The effectiveness of the sensors depends on the software, which bears the main burden in assuring the correct results. This makes it possible to compensate for variations in sensors and rig characteristics and effect complex non-linear algorithms.

Figure 4.9: Instrumented Rod





4.3 Instrumented Rod Subsystem

4.3.1 Overview

The instrumented rod sub-system is an instrumentation package capable of acquiring and relaying sensory information required to calculate drill bit deviation (see figure 4.9). It is designed for use in a down-hole hard-rock percussive drilling environment. The package is used in place of a normal drill pipe, located as close to the drill bit as possible. The sensory information is relayed to an uphole receiver via wireless transmission. The control sub-system then calculates the current position of the drill and alerts the operator if the drill has strayed more than a maximum distance from the required drill vector. The system can calculate the drill position in absolute mine coordinates if the rig position and orientation is known, or in coordinates relative to the rig if it is not. In addition if the dip and bearing of the required hole is known, then the distance between desired and actual position can be calculated and displayed as the deviation.

The typical requirements are to drill a 200 foot long hole within a maximum deviation of 2 feet, or 1 %. The drill pipe tends to drill fairly straight. However, if a fault or rock of different hardness is encountered, the drill will tend to deviate in the direction of least resistance. The drill will then progress in the new direction. This may occur several times and each deviation may be in any direction. We have no basis to assume that the direction will occur along a single plane, or even that it will be monotonic in shape. Although such an assumption simplifies the type of sensory input, it would result in a calculated deviation far greater than the actual deviation, and the decision to abandone drilling a perfectly acceptable hole.

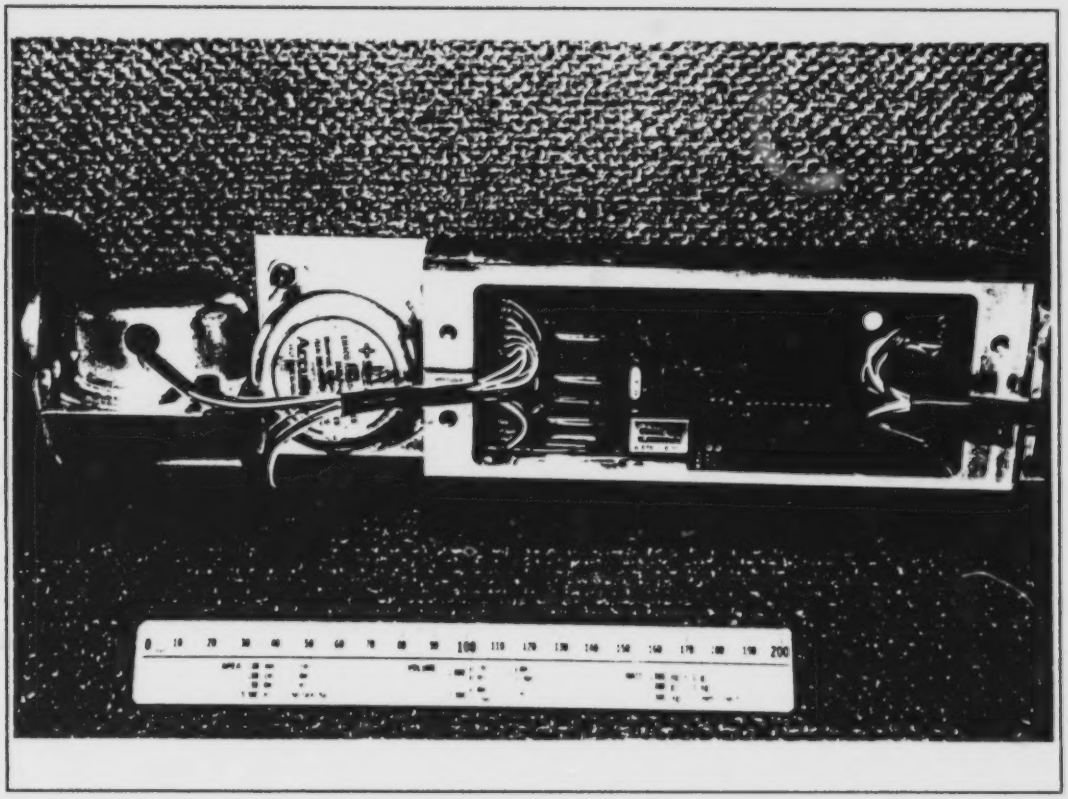


Figure 4.10

Instrumented Rod, Inclinometer sensors and processing electronics

The incremental position is calculated based on the incremental length of the hole and the drill vector for that pipe section. The length of the hole can be monitored at the rig. The drill vector can be measured by:

i) two single axis inclinometers (such as the Sperry Accustar), with resolution of .Ø1 degrees or better, mounted within the instrumented rod with their sensitive axis perpendicular to the gravity vector and to each other (see figure 4.1Ø).

ii) absolute drill pipe indexing angle whixh can be monitored at the drill rig, with a resolution of 1.5 degrees or better.

Given the two inclinometer readings Θ_1 and Θ_2, the pipe indexing angle Φ', and the length of the pipe L, then

$$\Phi = \tan^{-1}\left(\frac{\sin\Theta_2}{\sin\Theta_1}\right)$$, the instrumented rod relative rotation angle,

$R_z = \Phi' - \Phi - \emptyset_1$, where $\emptyset_1$ is the constant phase shift between the instrumented rod home and the rig home,

$$R_{xy} = \sin^{-1}\left(\frac{\sin\Theta_1}{\cos\Phi}\right) \quad \text{for} \quad 315 \leq \Phi < 45 \text{ and } 135 \leq \Phi < 225$$

$$= \sin^{-1}\left(\frac{\sin\Theta_2}{\sin\Phi}\right) \quad \text{for} \quad 45 \leq \Phi < 135 \text{ and } 225 \leq \Phi < 315$$

and the actual position of the leading end of the pipe as compared to the trailing end is

$$P_x = L \times \sin (R_{xy}) \times \sin (R_z)$$

$$P_y = L \times \sin (R_{xy}) \times \cos (R_z)$$

$$P_z = L \times \cos (R_{xy})$$

The actual absolute pipe position (relative to the drill rig) is

$$\sum_{i=1}^{n} (P_{ij}) \; ; \quad j = x, y, z$$

where n = total number of pipe sections, and P_i is the incremental position of the i'th pipe. The required position can be calculated in the same way using the dip (R_{xy}) and bearing (R_z) specified for the hole. The deviation error is the distance between the required point and the actual point.

Detailed development of the algorithm can be found in the appendices. A cartesian coordinate system is specified, along with a corresponding polar system which describes the position of the drill in terms of length, dip (or inclination) and bearing, which are simpler to calculate. The rotation of the pipe and the instrumentation package it contains is related to the static coordinate system. A total of four variables are required to uniquely identify the position of the drill pipe.

The effect of measurement error due to limited sensor resolution and sensor drift is also examined in the appendices, yielding a set of requirements for the sensors.

The Instrumented Rod Subsystem (IRS) forms an integral part of the Down-the-Hole (DTH) Drill Automation System developed by VADEKO International. It enables the system to obtain orientation data from the leading end of the drill string, from which the trajectory of the drill hole can be tracked (see figure 4.11). This information allows the system to detect excessive deviation of the drill bit from the intended hole dip and bearing, and alert the operator to the error condition. The operator will then decide whether or not to abandon the drilling of that hole.

The data acquired by the IRS consists of the angle between the instrumented rod assembly and the gravity vector along two perpendicular axis. This must be combined with data from the Drill Hydraulics Subsystem and the Rig Setup Subsystem, and processed by the Controller Subsystem to calculate the hole trajectory. Data is acquired from the IRS during the time while a new pipe is added to the drill string. The drill string is not turning or under stress, drill air is off, and the string is broken allowing access to the inside of the pipe.

The IRS is divided into two separate assemblies: the up-hole assembly, and the down-hole assembly, normally referred to as the instrumented rod assembly (IRA). The IRA is externally very similar to a normal drill pipe: it has the same dimensions and threads, and allows the passage of drill air with minimal pressure drop. Internally however, it contains the instrumentation and communications package which adds approximately 30 lbs. to the weight of the rod. The IRA is added like any normal drill pipe, as close as possible to the hammer, typically following a short stabilizer. The rod contains its own power supply (which lasts a minimum of 4-5 holes between

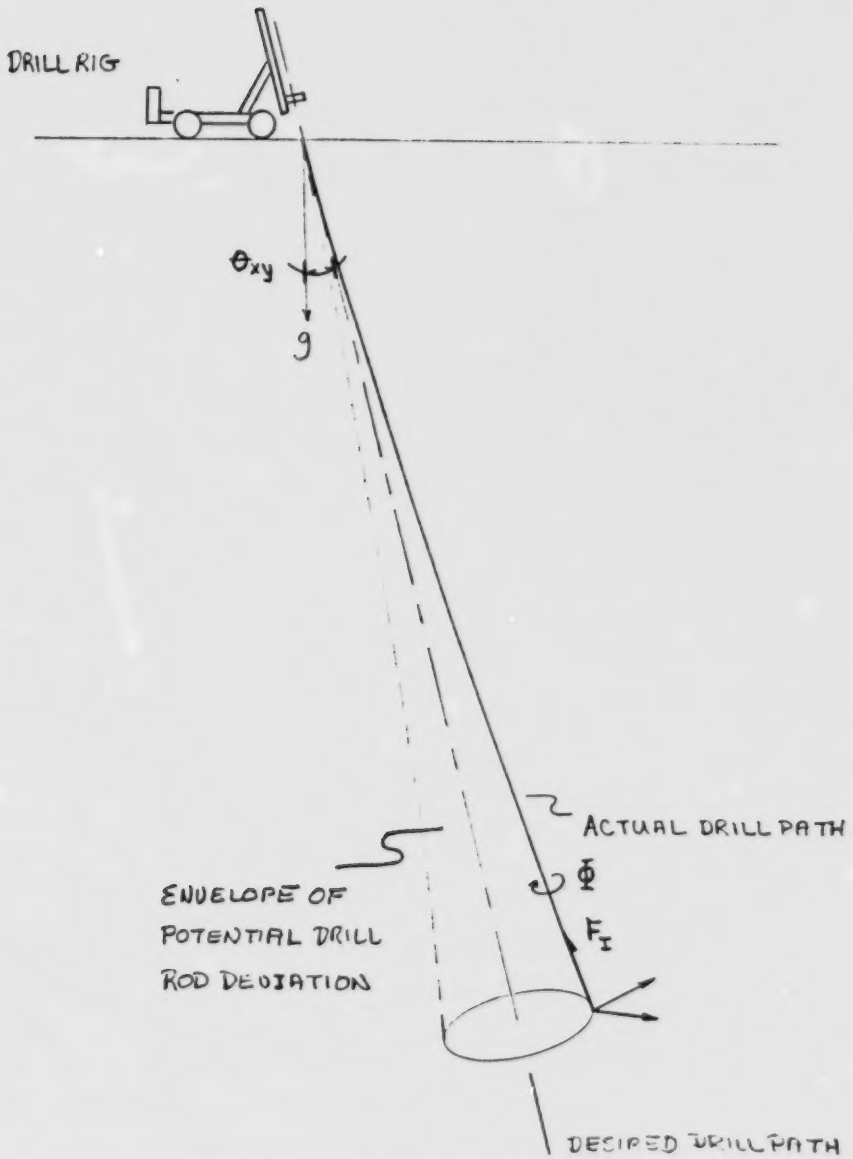


Figure 4.11

Drill Rod Path Deviation Due to Rod Compliance

rechargings), sensors, processing electronics, and a microwavetransmission link with which it communicates through the inside of the pipe to the up-hole assembly. The up-hole assembly is a rugged device, attached to the rig which the operator swings out and places over the drill pipe hole after breaking the drill string, and which establishes the communications link between the IRA and the Controller Subsystem.

The IRA consists of an instrumentation package mounted on a shock-reduction system. The instrumented package consists of (see figure 4.9):

1) sensors: two Sperry Accustar Inclinometers, sensitive to 0.001 degree.

2) power supply: two rechargeable gel-cell batteries, DC-DC converters and shut-down control.

3) processing electronics: convert the two pulse-width encoded signals from the inclinometers to a serial data stream.

4) microwave transmission: convert the data stream to a 15mW, K-band (24.150 Ghz) signal for transmission to surface, and the reverse.

The four component subsystems are mounted on a solid core for ruggedness and encased in an outer protective sleeve. The only servicing possible by an operator is to recharge the batteries. Any failures require service by trained personnel. However, disassembly, service and reassembly is simple, due to the design of the locking devices used and the modular design approach.

4.3.2 Sensors

The sensing elements used in the IRA are two miniature electronic inclinometers. The manufacturer and type is Sperry Accustar. These devices sense gravity and produce an output proportional to the angle of rotation about their single sensitive axis. Two devices are bolted to the core at a right angle to each other along the core's axis. If the rod is exactly upright, both devices will output zero and not sense rotation of the pipe. Tilting of the rod from the vertical produces an output from each which will depend on the component of tilt in each of the two horizontal axis.

The sensor works on the principle of varying capacitance with the angle. This is done by a sandwich of two circular plates separated by a fluid which acts as a dielectric. Each plate is actually split in the middle, forming two semi-circular capacitors. When the sensor is upright, i.e., the split in the plates is vertical, the fluid only covers half of each plate pair. As the device rolls along its edge, the fluid will cover proportionally more of one pair of plates, and less of the other, thus varying the two capacitances in an equal and opposite way. This results in a very linear variation in capacitance with angle and no moving parts. The variation in capacitance can be converted to an analogue output voltage. For the IRA, a digital output model was chosen. In this case, each capacitative plate forms part of a timing circuit, so that two output pulses are available whose length is proportional to the angle. Two additional pulses are generated: a delta pulse whose duration corresponds to the difference in the pulse widths, and a direction signal which indicates which of the two pulses is the shorter by whether or not it is active. It is these latter two additional pulses which are used. It is theoretically possible to establish a zero point where the two capacitances and electronic circuits balance exactly. At that point the delta

width pulse would be infinitely short, in fact non-existent.

The resolution of the inclinometer is .001 degrees. Linearity is guaranteed to be accurate to +/- 1 percent of angle over a range of +/- 45 degrees, with a monotonic increase in error up to the full range of +/- 60 degrees. Cross-axis error, caused by tipping the capacitative plates towards their flat sides, is guaranteed less than 1 percent up to a tip of 25 degrees. In fact, an independent test and analysis of several typical production units showed that linearity and cross-axis error were within spec up to +/- 50 degrees from vertical. Algorithms in the controller subsystem will be applied to the data to compensate for these errors to the required accuracy.

A short trigger pulse of duration .5 to 10 microseconds must be initially applied. Some milliseconds later, the delta pulse will become active for a duration of 0.6 milliseconds per degree of rotation. The direction of rotation is valid any time after the start of the delta pulse. The entire sequence can be repeated at a maximum rate of 50 times a second.

Sensitivity of the devices to temperature variations is very low: degree centigrade of change in environmental temperature. The mine air does not undergo very large swings in temperature, and the high air flow required for drilling will minimize temperature variations in the rod.

The sensor and electronics are encased in a rugged, watertight housing.

4.3.3 Electronics

Power is needed in the IRA to power the sensors, the processing electronics and the microwave transmitter/receiver. The sensors and microwave receiver require minimal power. The transmitter

requires 200 mW when operating. A packet of data is transmitted on request up to 5 times per sampling (a set of samples is taken once per pipe added). If the data is received the first time, there is no need to re-transmit. This approach minimizes power consumption. The processing electronics consume about 250 mW of power, and since they control the IRA activity and must remain active whether or not transmission is taking place, will consume the greatest amount of power. Several steps have been taken to minimize this. Apart from minimizing power consumption within the electronics by design (using CMOS technology over bipolar where possible), two mechanisms are used to shut off power completely: an air pressure switch which only is closed only when the pressurized drill air is not present, and a power shutdown circuit controlled by a signal generated by the processor after it has succesfully transmitted data, or has unsuccesfully attempted to transmit data 5 times, or after a maximum time delay, typically about 2 minutes. Once power is shutdown, the processor or any other part of the IRA cannot turn itself back on until drill air is reapplied and removed. The trade-off is that the operator must establish contact with the IRA within two minutes of turning off drill air. Normally a two minute delay is more than twice the required time.

The source of power is two rechargeable sealed gel-cell type batteries, each supplying 1.0 Ahr at 6 volts. Under typical operating conditions, this will provide power for a minimum of 4 holes before recharging becomes necessary. Recharging is a simple procedure which the operator can do. Provided 115 VAC is available, a standard 6V battery charger is connected to a recharge port within the IRA via a special self-aligning plug, and left for a shift.

A function of the power supply electronics is to provide the required voltages to the various components. The processing electronics require 5 volts +/- 5% at .25 A typ/ .4 A max. The inclinometers require +8 to +20 volts (12 volts nominally) at 5

ma typ. The microwave transmitter can use the 5.5-6V output of the battery directly, but the high-gain low-noise receiver amplifiers require both a positive and a negative supply, approximately +/- 12 volts at 50 ma. A voltage doubler circuit provides 11.3 volts from the 6 volt source, and a negative voltage generator circuit flips this to -10.7 volts. A zener diode limits the processor's voltage to 5 volts. The fairly constant power requirements allow choosing a dropping resistor that minimizes power waste.

The air pressure switch is connected directly in series with the batteries. With drill air pressure present, power is completely cutoff. When the drill air is absent, power flows through the switch and through the normally closed contacts of the shutdown relay to the rest of the circuits. When a shutdown signal is received from the processor, the shutdown relay is activated, cutting off power to the rest of the circuit, but closing a second pair of normally open contacts which ensure the relay remains on, effectively latching the shutdown signal. Power consumption is now limited to the few milliamps required by the relay. The circuit is only reset by the complete removal of power, caused by the air pressure switch opening.

Processing Electronics

The processing electronics are based on a ZILOG Z-8 single chip micro-computer. This device contains 2K ROM, 124 bytes RAM, serial port (UART), 2 counter/timers, and 14 bits of parallel I/O ports, all on a single chip. The version of Z-8 chosen, the Z8671, contains a small BASIC language interpreter in its ROM. Memory must be added externally to contain the application program. The use of the BASIC interpreter allows simple programs to be written, tested and modified quickly and easily. Time

critical parts of the program, such as the generation of the very short trigger pulses required by the inclinometers, can be written in machine code, and called as subroutines by the mainline.

The application code is stored in external memory. For initial development it is convenient to be able to change the code easily, and for this reason, RAM (Random Access Memory) is used. A small editor within the BASIC interpreter allows programs to be created and modified in RAM. Since this type of device "forgets" when power is removed, a special RAM device was used that contains its own battery to retain memory contents when power is removed. Although this keeps the data for up to several years, it is always subject to accidental modification of the RAM contents, and the more permanent EPROM (Eraseable Programmable Read Only Memory) device replaces the RAM in the final implementation.

The data stream sent/received by the on-chip UART (Universal Asynchronous Receiver Transmitter) consists of 10-bit frames. This means that 10 bits of information are sent one after another, each lasting one bit-time. A bit-time is simply the time between subsequent bits of information appearing at the output/input of the device. This is controlled by an internal clock and determines the rate at which data is sent: the "baud" rate. Once a frame is sent, the output remains in an active state, marking time as it were, hence the term "mark" state, until another frame of information is sent/received some unspecified time later. Clearly the frame must define its start with a bit of opposite polarity to the mark state, and this is called the start bit. Since the clocks controlling the transmitter and receiver are not synchronized, it is the transition of the start bit that re-synchronizes the two clocks. In this case, after the start bit, 8 data bits are sent, of which 7 bits are used to represent the data as an ASCII encoded character, and the 8th bit is the parity. After the data parity

bit comes as stop bit, which is always at the mark state, and ensures that at least one bit time is spent at the mark state should another frame begin immediately after the current one. Data representing the inclinometer readings is sent as a string of ASCII characters, '0' to '9', '.', and preceeded by '+' or '-'. Additional characters are used to tag the pieces of data and help detect transmission errors. This is referred to as the protocol of the transmission and is detailed later. Encoding data as an ASCII string increases redundancy (which helps detect errors) and enables a standard terminal to be used during development and debug.

The clock for the UART is generated internally by dividing the crystal-based clock that drives the processor by a number that gives the required baud rate. One of the counter/timers can be programmed to use the main clock as input and output to the UART directly. The data rate used is 110 baud, or bits per second. With an 11-bit frame this corresponds to 10 characters a second. This is very slow indeed compared to the capacity of the microwave link, thus again increasing transmission reliability, but is also more than fast enough for our purposes since an entire data message can be sent in less than 5 seconds. With the 7.3728 Mhz clock used by the processor, a two stage division by 3 and then by 175 will generate the required serial clock.

The inclinometer triggers are generated by software pulsing of one of the parallel digital output bits. A decoder chip "steers" the trigger to the inclinometer chosen by an "address" bit, also output via another processor output bit. The pulse generated as output by the inclinometer cannot be measured directly by the software to the desired resolution. Therefore, the pulse is converted into a series of pulses of high frequency, and counted by a combination of an external high speed counter and the internal counter in the processor. A second crystal based clock of 10 Mhz is used, yielding a pulse timing resolution of 100 ns. This pulse train is divided by an 8 bit counter, or 256, and then

fed to the processor's internal timer at a frequency of about 39 Khz. When the pulse is finished, the software reads the contents of the internal counter and of the external counter via 8 bits of its digital input port. The direction bit is also fed to an input port and read by the software. The same address bit that steered the trigger also selects from which inclinometer the pair of output signals will be chosen to drive the counter and processor.

When power is applied, the Z-8 is reset and then begins executing the program in external memory. An outline of the functions is as follows:

1) initialize the serial and parallel ports of the Z-8, and initialize the second timer/counter to determine elapsed time.

2) wait for a data request message to be received via the microwave link, or until a timeout has elapsed. If a timeout has elapsed, activate the power shutoff line.

3) if a data request message is received, then reconfigure the second counter for angle measurement. Take four samples alternately from each of the two inclinometers and average the data to obtain the two angle readings. Output the data via the serial port to the microwave link for transmission to the up-hole assembly. The data packet will contain additional error detection data.

4) wait for a data acknowledge message to be received via the microwave link, or a (shorter) timeout has elapsed. If the data was received with errors, then another data request message is sent by the controller subsystem, and the cycle repeats. Otherwise, the power shut-off line is activated.

The communications protocol over the microwave transmission link consists of multi-character messages of the following types:

1) **Link Test Prompt**

Originator: up-hole transmitter

Purpose: to determine if the IRA is functional and the communications link established.

Syntax: "?"

Response: Link Test Response

2) **Link Test Response**

Originator: down-hole transmitter

Purpose: to answer a Link Test Prompt and establish that the communications link is functional.

Syntax: "!"

3) **Data Request**

Originator: up-hole transmitter

Purpose: commands the IRA to sample the two inclinometers and transmit the data.

Syntax: "D"

4) **Data Message**

Originator: down-hole transmitter

Purpose: transmits the current inclinometer readings to the up-hole receiver/ controller subsystem.

Syntax: "D A +12.345 B -6.789 <LF> xxxx <CR>"

note: i) spaces are not processed and may be inserted between items

ii) <LF> represents the ASCII line feed control character

iii) <CR> represents the ASCII carriage return control character

iv) xxxx represents a binary coded decimal (BCD) encoded checksum of the complete string using "0"-"9", "a"-"f".

5) **Data Acknowledge**

Originator: up-hole transmitter

Purpose: to acknowledge to the IRA the receipt of a data message, and indicate whether or not errors were received

Syntax: "AØ" if no errors received

"A1" if errors received

4.3.4 Signal Transmission

Communication between the IRA and the up-hole assembly is accomplished by a microwave link through the inside of the drill pipe. The serial data output by the UART of a transmitter (see figure 4.12) is converted into bursts of microwave energy that travel along the inside of the pipe until they are received and converted back into a serial data stream for the receiving UART. The inside of the drill pipe acts as a waveguide for the energy. This technique was chosen because it is not sensitive to the metallic content of the ore, because there is no background noise to contaminate the signal, and because it is not effected by the curvature of the pipe.

To waveguide electromagnetic energy, the wavelength of the energy must be less than the width of the guide. The narrowest parts of the drill stem are at the pipe threads, where an inside diameter of 1.75 inches is encountered. This corresponds to a minimum cutoff frequency of 6.75 Ghz. The devices chosen use the standard K-band frequency of 24.150 Ghz, and create a waveform of circular "shape" or polarization. Since this wavelength is much shorter than that of the cutoff frequency, it can "fit" into the waveguide in several ways. It is a common characteristic of waveguided electromagnetic energy that it simultaneously travel

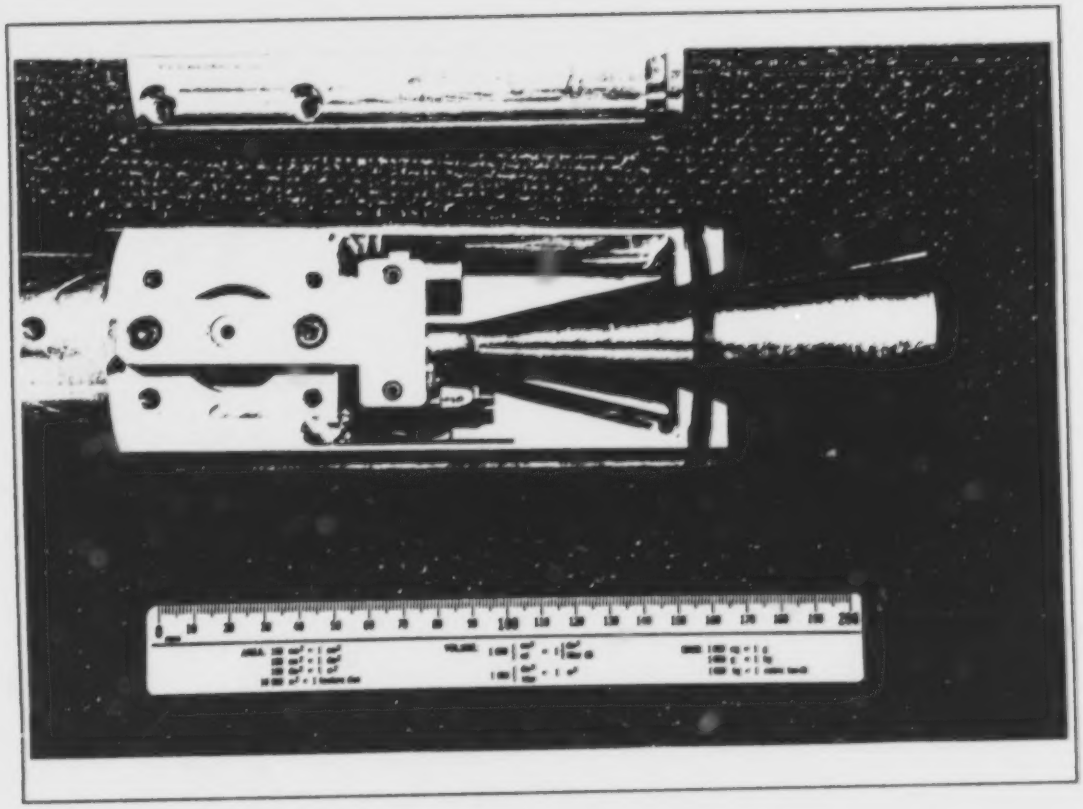


Figure 4.12

Microwave Antenna and Transmitter in Instrumented Rod

in several "modes". Where the drill pipe is at its maximum width, more modes of transmission can exist, and it is this "rearranging" of energy and subsequent interference at each pipe interface that accounts for much of the signal loss.

The source of the microwave energy is a 15mW Gunn Oscillator diode, connected to a circular polarized horn antenna. The diode is mounted in a resonant cavity which acts as a heat sink and determines the frequency of oscillation by its size. This is set at the factory and cannot be adjusted. When 5.5 to 6 volts are applied to the diode, it emits microwave energy. A pulse train of microwave energy can be generated by switching on and off the power to the diode. This is accomplished by a MOSFET device which converts the low-power 5 volt output of the processor to a high-power 6 volt signal. It acts essentially like an electronically controlled switch.

The energy is picked up by a horn antenna (in fact the same antenna is used for both transmit and receive) and fed to a Schottky Receiving diode, where it is converted into a current. The microwave energy undergoes a loss of about 110db (1/300,000th of the transmitted signal strength) with the maximum pipe length of 200 feet, so that the output of the diode can be 10 microvolts or less. Therefore it is necessary to first amplify this signal with low-noise instrumentation amplifiers. The signal is then compared to a threshold value and converted into a digital 5 volt signal suitable for the UART.

The up-hole assembly provides the link between the IRA and the controller subsystem. It is swung into position by the operator before a new drill pipe is added. The microwave link is established and data from the IRA transmitted to the controller. The up-hole assembly is essentially the same as the microwave transmission section of the IRA. However, the receiver output is converted to +/- 12 volts to be compatible with the standard RS-

232C serial ports available on the controller. In addition, a proximity sensor indicates to the controller when the assembly is in position over the drill pipe. The electronics are very ruggedly encased in order to survive handling.

4.3.5 Packaging

As previously described, the four major IRA components are bolted to a core (see figure 4.9). This is a solid single piece of aluminium, 2.75 inches in diameter, with flats and chambers machined out to contain the components. With the exception of the inclinometers, the remaining items are mounted with a further degree of shock absorbency. The two electronic assemblies, the processor and the power controller/ microwave transceiver, are potted in a hard epoxy compound, and bolted via integral studs and shock absorbers to the core. The batteries and the microwave antenna/diodes are suspended in foam and rubber within their respective chambers.
The core is housed in an outer sleeve that provides environmental protection. It slides off easily for service. O-ring seals are used to seal between the core and sleeve. Vent holes are required to ensure excessive pressure differential does not build up between the inside and outside of the sleeve when 250 psi drill air is applied.

The microwave antenna is covered with a thin plastic lid impervious to water and dust. A second dome forms an integral part of the sleeve and affords the primary protection for the microwave diodes. The dome is formed from nylon causing minimal attenuation to the microwave energy.

The core and cover together form the instrumentation package that must be protected from the high shock of the drill bit impacting the rock, and the high vibration caused by the hammer and bit

movement. A low frequency damped air shock absorber is used to connect the core/sleeve to the modified drill pipe. This device absorbs shock along the axis of the pipe. Its transmissibility falls off quickly above 3 hz, while the main vibration components are believed to be in the 5-7 hz range, the rate at which the bit impacts the rock. The alignment of the core is maintained by mounts at the top and bottom which allow movement along the axis of the pipe in order for the shock to be absorbed. Towards the top of the sleeve, three groove and pin mechanisms guide the sleeve. At the bottom, the shaft connecting the core to the air shock slides through a rubber grommet that also provides protection against lateral high-frequency shock.

To gain access to the inside of the instrumented drill rod, a special tool is used to first remove a locking mechanism. A threaded connection may then be undone to expose the inside of the pipe. The core and sleeve are then simply slid out.

At the bottom end of the assembly, below the air shock, is the recharge port, in a small centered cavity that is little exposed to the passing drill air. By using a self-centering guide, an operator may engage the connector and recharge the batteries.

4.3.6 Summary

The instrumented core has proved to be very rugged in actual drilling conditions. The design performs as required, but also makes future expansion possible. Other kinds of sensors can be easily integrated with only minor changes to the hardware. More complex data acquisition algorithms or communications protocols can be implemented by simply changing the firmware. At present, a subset of the protocol described in this section is being used that requires only one-way communication. Two-way communication

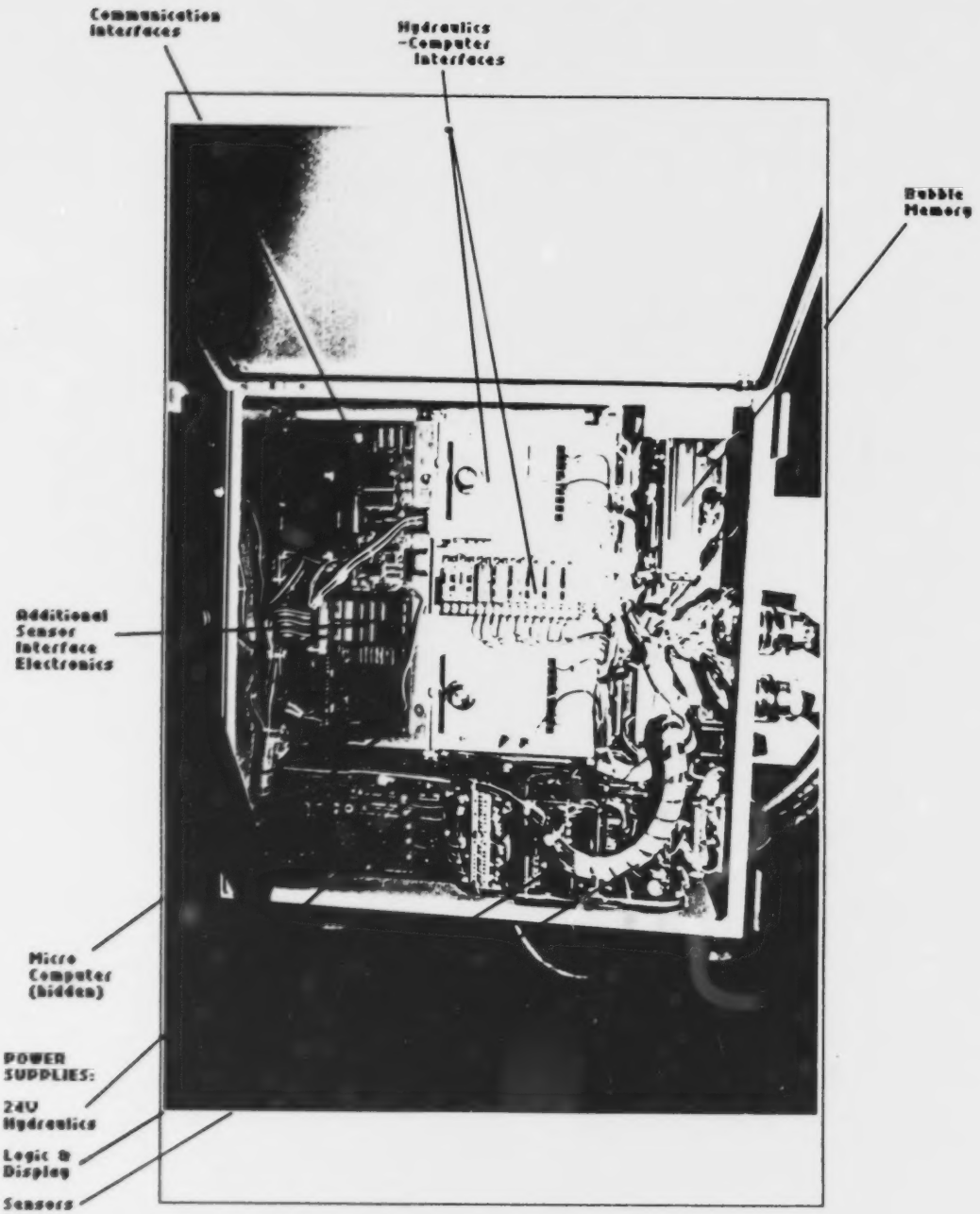


Figure 4.13

Controller Subsystem

offers more immediate re-transmission of data and lower power consumption, but present results indicate one charge may last at least 4 holes, making that issue secondary.

4.4 Controller Subsystem

4.4.1 Overview

The Controller Subsystem (CS) (see figure 4.13) is the heart of the system. It contains the power supplies, sensor signal processing, output signal buffering, bubble memory device and control computer. Included in the subsystem is the operator display panel, though it is a physically separate assembly.

4.4.2 Computer Hardware/ Firmware

All functional control resides in the CS controller, an ETI 8640 microcontroller. This single board computer consists of an INTEL 8088 microprocessor, up to 56K bytes of user RAM/program memory, an 8087 floating point processor for fast calculation of complex numeric functions, 4 RS-232 serial ports, and I/O interfaces including 16 bits of digital input, 16 bits digital output, 8 analog inputs, 2 analog outputs and four high speed accumulators.

To simplify software design, the controller includes a firmware EPROM which supports real-time multi-tasking, memory management, communications channel management, and management of its I/O capabilities. All functions are accessed via a software interupt using parameters in registers, making integration with high level languages simple.

4.4.3 Software Development

Software has been developed on an IBM PC, using the ACCESS -86 software package by GENESIS microsystems. This software allows INTEL's UDI-based 8086 developement software to run on the IBM personal computor. The development system includes assemblers, high-level language compilers, linker, loaders, etc, targetted to the INTEL 8088/86 used by the ETI 8640. Only a minimal amount of code was written in assembler: that required to link the high-level language calls to the system firmware, and math routines using the 8087 floating point processor. The majority of the software was written in PL/M high-level language.

The resultant complete binary program image is converted to the INTEL HEX format and downloaded to the ETI 8640 via a terminal emulation program supplied by ETI which runs on the PC. This is an ideal environment for prototype development as it allows debug to be carried out in the field quite easily. When program development is complete, the code can be downloaded to an EPROM burner (just like downloading to the 8640) and burned into EPROMs which are then installed in place of program RAM on the 8640.

4.4.4 Operator Interface Assembly

The operator interface assembly comprises the following devices:

1.Operator function keys: these four keys are the operator's primary input to the controller. The functions performed when the keys are pressed depend on what the operator is doing, i.e., the mode of the system. The functions are clearly indicated on the display, changing as required. Such a menu-driven system is less confusing than a large array of all possible buttons.

2.Keypad: a 4 x 4 array of keys for occasional numeric input.

3.Emergency stop button.

4.Operator panel display: a plasma panel (see figure 4.1) manufactured by DALE (APD-256M026) has been used due to its small size, high ruggedness and brightness. It has 8 lines of 32 characters which allows clear unambiguous messages and instructions to be displayed to the operator, as well as readout of sensors. The device has self-contained character generation, refresh and serial interface making integration with the system very simple.

4.4.5 Bubble Memory Assembly

A TARGA bubble memory cartridge system is used to transfer survey information for use by the Rig Setup Subsystem, and for storing drill performance data. The entry and retrieving of information is done at the office. The cartridges have a memory of 128 to 512 Kbytes, and the unit interfaces as an RS-232 device, making integration into the system relatively simple.

5 Recommendations and Future Development

As with any prototype engineering system, a number of design improvements have been identified as a result of the field trials. The lack of any major or fundamental system failures is a strong indication that the level of technology is suited to the problem and environment.

The field tests must be continued before the final verdict can be passed on the system as a commercializable unit. These tests should be completed before all the requirements for a second iteration design phase can be identified.

A number of results are inconclusive because the actual operating test conditions varied widely from those established as 'typical' by our mining contacts early in the project. Boosted air at 250 psi was not available during the field tests and is fundamental to the operation of such functions as automated drilling and the use of the instrumented rod. Since the trend in the industry is towards boosted air as originally established, it does not seem worthwhile to expand the design parameters to include 80 psi mine air. However, further testing should be conducted at boosted air pressure to be of any value.

Another fundamental deviation from the original problem definition is in the amount of water used while drilling. Since the rod was designed for a much smaller amount of water than what was used in the field tests, penetration of water into the rod caused severe reduction in the power of the microwave transmitter, and would eventually lead to its failure. Further tests should use almost dry drilling to verify operation and transmission capability. If an extremely moist environment is identified as a necessary part of the problem definition, additional engineering will be required to the instrumented rod.

During field testing of the automated drilling functions, the major problem encountered was stalling of the rotation drive. With a controlled rotation rate lower than the full rotation rate used by the miner under manual control, the penetration rate appeared to be greater. However the increased chip volume combined with insufficient air to clear the chips from the bit (only 80 psi mine air was available) is suspected to have caused 'muddying' of the bit, and subsequently a stall condition. Two potential problems should be addressed here. First, the automatic hydraulic system has a maximum rotation rate of 27 RPM which is beyond the range that miners 'typically' use. In fact it is more common for the miners to simply use full rotation rate of 38-40 RPM resulting in a sub-optimal rotation rate, but less problems with bit muddying and subsequent stalling. It may be necessary to improve the rotation hydraulics to achieve full power. Secondly, the drilling problem appears at this time to be far more complex that simply maintaining a constant rotation rate and drill pressure. These two objectives WERE achieved, and yet this was not sufficient to adequately drill under automatic control. It seems the algorithm to control drilling is very much more complex and in fact represents a project in itself. It should be noted that the controller HAS THE CAPACITY to be reprogrammed to support such algorithms. Boosted air may be enough to eliminate the problem of inadequate chip removal. Unfortunately, since boosted air was not available, further tests are required before the problem can be identified.

The minor failures experienced during testing suggest the following design improvements should be undertaken:

- the feed position encoder sensor bracket should track the feed encoder bar to automatically compensate for relative positional shifts. The bracket should be lengthened to prevent binding and perhaps spring loaded against the encoder bar.

- although a properly bonded rotation sensor ring seems to be surviving well, the concept could be designed right into the rotary head itself to guarantee its long term survival.

- all cabling to the various sensors and actuators, though sufficiently rugged for a prototype, should be made more rugged in a commercial unit. The use of hydraulic hose to house electrical cable is now common in the industry.

- to increase the accuracy of the rig setup system laser, it is necessary to have the ability for the operator to quickly and easily re-calibrate the device. A couple of permanent calibration points, welded to the rig, and appropriate software should solve this problem.

Performance results are detailed in the appropriate subsections of the design description - section 4.

Appendices

A.1 Conversion from Cartesian to Polar 3-D Transform

-given a left-handed cartesian coordinate system, where the positive Y axis defines the front of the rig, the positive X axis the left side, and the positive Z axis points upwards (see figure A.1.1),

- assume a unit vector that forms an angle θ_{cx} to the positive X axis and an angle θ_{cy} to the positive Y axis,

- the unit vector is equivalently directed by the angle θ_{cxy} to the XY plane, and the angle θ_{cz} formed by the projection of the vector onto the XY plane and the positive Y axis.

- then the length of the projection on the unit vector on the XY plane is

$$\cos\theta_{cxy}$$

and the components of the vector on the X, Y, and Z axis are

$$L_x = \cos\theta_{cxy} \times \sin\theta_{cz}$$
$$L_y = \cos\theta_{cxy} \times \cos\theta_{cz}$$
$$L_z = \sin\theta_{cxy}$$

- therefore

$$\tan\theta_{cx} = \frac{L_z}{L_x} = \frac{\sin\theta_{cxy}}{\cos\theta_{cxy} \times \sin\theta_{cz}} = \frac{\tan\theta_{cxy}}{\sin\theta_{cz}}$$

$$\tan\theta_{cy} = \frac{L_z}{L_y} = \frac{\sin\theta_{cxy}}{\cos\theta_{cxy} \times \cos\theta_{cz}} = \frac{\tan\theta_{cxy}}{\cos\theta_{cz}}$$

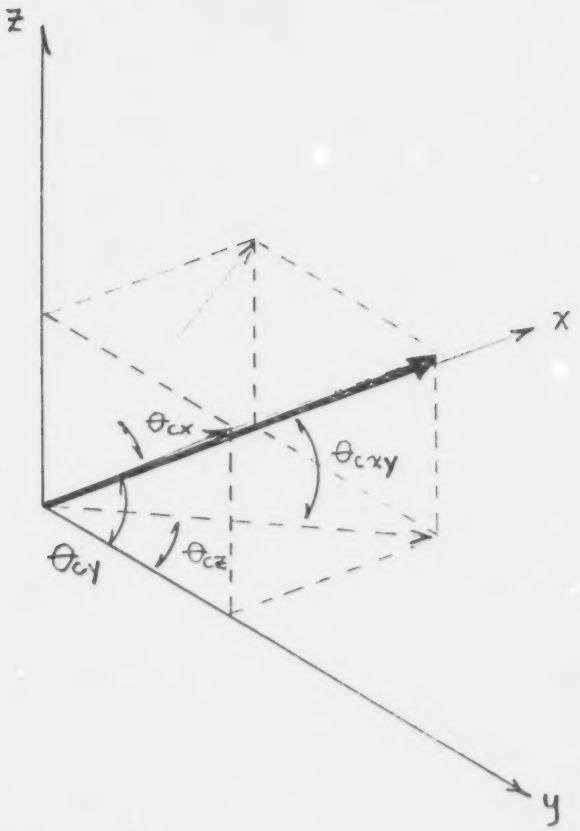


Figure A.1.1

Conversion From Cartesian
To Polar Coordinates

- rearranging, we get

$$\sin\theta_{cz} = \frac{\tan\theta_{cxy}}{\tan\theta_{cx}}$$

$$\cos\theta_{cz} = \frac{\tan\theta_{cxy}}{\tan\theta_{cy}}$$

yielding

$$\tan\theta_{cz} = \frac{\sin\theta_{cz}}{\cos\theta_{cz}} = \frac{\tan\theta_{cxy}}{\tan\theta_{cx}} \times \frac{\tan\theta_{cy}}{\tan\theta_{cxy}} = \frac{\tan\theta_{cy}}{\tan\theta_{cx}}$$

and then

$$\tan\theta_{xy} = \cos\theta_{cz}\tan\theta_{cy} = \sin\theta_{cz}\tan\theta_{cx}$$

A.2 Rig leveling calculations and Rotation Matrix

- rotation by θ about Z axis:

$$\begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- rotation by θ about X axis:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix}$$

- combining 1) rotation about Z axis by $-\theta_{cz}$
  2) followed by rotation about X axis by θ_{cxy}
  3) followed by rotation about Z axis by $+\theta_{cz}$

yields

$$[R_1]([R_2][R_3])$$

$$= [R_1] \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{cxy} & \sin\theta_{cxy} \\ 0 & -\sin\theta_{cxy} & \cos\theta_{cxy} \end{bmatrix} \begin{bmatrix} \cos\theta_{cz} & \sin\theta_{cz} & 0 \\ -\sin\theta_{cz} & \cos\theta_{cz} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} \cos\theta_{cz} & \sin\theta_{cz} & 0 \\ -\sin\theta_{cz} & \cos\theta_{cz} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_{cz} & \sin\theta_{cz} & 0 \\ -\cos\theta_{cxy}\sin\theta_{cz} & \cos\theta_{cxy}\cos\theta_{cz} & \sin\theta_{cxy} \\ \sin\theta_{cxy}\sin\theta_{cz} & -\sin\theta_{cxy}\cos\theta_{cz} & \cos\theta_{cxy} \end{bmatrix}$$

$$
[Rm] = \begin{bmatrix} \cos^2\theta_{cz}+\cos\theta_{cxy}\sin^2\theta_{cz} & & -\sin\theta_{cz}\sin\theta_{cxy} \\ & \cos\theta_{cz}\sin\theta_{cz}-\cos\theta_{cxy}\sin\theta_{cz} & \\ \sin\theta_{cz}\cos\theta_{cz}-\cos\theta_{cxy}\cos\theta_{cz}\sin\theta_{cz} & & \cos\theta_{cz}\sin\theta_{cxy} \\ & \sin^2\theta_{cz}+\cos\theta_{cxy}\cos^2\theta_{cz} & \\ \sin\theta_{cxy}\sin\theta_{cz} & & \cos\theta_{cxy} \\ & -\sin\theta_{cxy}\cos\theta_{cz} & \end{bmatrix}
$$

A.3 Calculation of Conic Symmetry Point

- given the two survey points, P_1 and P_2, and the two elevation angles Θ_1' and Θ_2', we wish to calculate the Z value of the point of intersection on the plane of symmetry, P_{sz}. The three points exist on a plane forming a triangle. The line from P_1 to P_2 has length L, from P_1 to P_{sz} length L1, and from P_{sz} to P_2 length L2. We will use the length to name the lines (see figure A.3.1).

Let $\measuredangle_1$ be the angle of L from the horizontal, then

$$\sin(\measuredangle_1) = \frac{P_{2z}-P_{1z}}{L}$$

and

$$\cos(\measuredangle_1) = \frac{L_{xy}}{L}$$

where $L = \mathrm{SQRT}((P_{2x}-P_{1x})^2 + (P_{2y}-P_{1y})^2 + (P_{2z}-P_{1z})^2)$,

and $L_{xy} = \mathrm{SQRT}((P_{2x}-P_{1x})^2 + (P_{2y}-P_{1y})^2)$, the length of L projected on a horizontal plane.

Let $\measuredangle_2$ be the angle between L and L_2, then since the interior angles of a triangle sum to 180 degrees,

$$\measuredangle_2 = 180 - (\measuredangle_1+\Theta_1) - (180-\Theta_1-\Theta_2)$$
$$= \Theta_2 - \measuredangle_1$$

Now by the law of sines

$$\frac{L1}{\sin\alpha_2} = \frac{L2}{\sin(\theta_1+\alpha_1)} = \frac{L}{\sin(180-(\theta_1+\theta_2))}$$

giving

$$L2 = \frac{L \times \sin(\theta_1+\alpha_1)}{\sin(\theta_1+\theta_2)}$$

Now, using one of the sides,

$$P_{sz} = P_{2z} - L2\sin\theta_2$$

$$= P_{2z} - \frac{L(\sin\theta_1\cos\alpha_1 + \cos\theta_1\sin\alpha_1)\sin\theta_2}{\sin(\theta_1+\theta_2)}$$

$$= P_{2z} - \frac{L(\sin\theta_1(L_{xy}/L) + \cos\theta_1((P_{2z}-P_{1z})/L))\sin\theta_2}{\sin(\theta_1+\theta_2)}$$

$$= P_{2z} - \frac{L_{xy}\sin\theta_1\sin\theta_2 + (P_{2z}-P_{1z})\cos\theta_1\sin\theta_2}{\sin(\theta_1+\theta_2)}$$

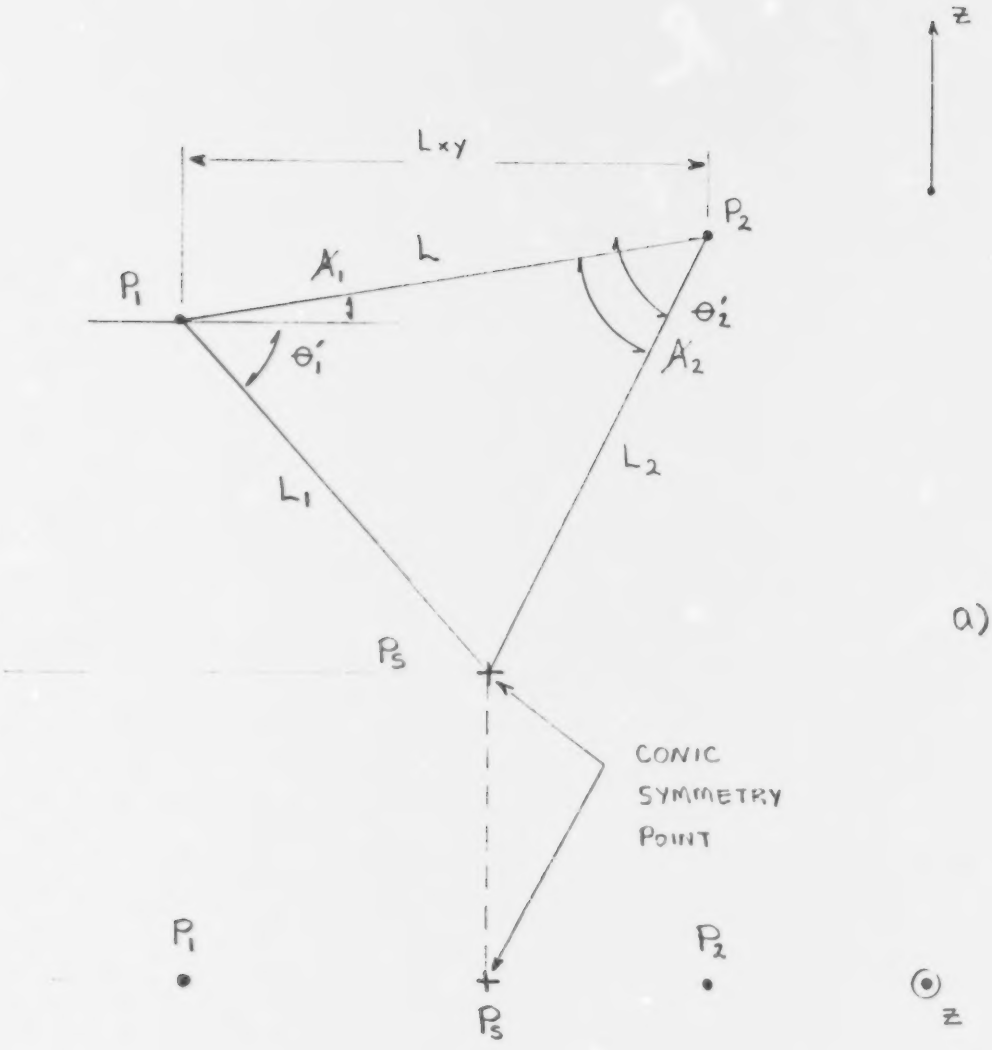


Figure A.3.1

Determination of Conic Symmetry Point, Psz

A.4 Calculation of Required Mast Angles

The relationship between the required drill vector, (Θ_{dp}, Θ_{az}), and the required mast angles (Θ_{er}, Θ_{sw}) is derived by representing each process by transforms on a unit vector. The two resulting vector endpoints must be equivalent. The drill vector is described by absolute angles, and must be mapped to the rig's coordinate system in order to coincide with the mast angle transforms. Since the rig's absolute azimuth is known, $\Theta_{rig\ az}$, the drill vector is mapped to (Θ_{dp}, Θ'_{az}) where

$$\Theta'_{az} = \Theta_{az} - \Theta_{rig\ az}.$$

First we start with the unit vector representing the vertical mast, $U_1 = \{ 0,0,1\}$. Since the swing mechanism is effected by the erection mechanism, mast setup is represented by first rotating by Θ_{sw}, then by Θ_{er}. Using matrix notation, the mast vector U_m, is calculated as

$$\{U_m\} = \{U_1\} [R_{sw}] [R_{er}]$$

$$= \{0\ 0\ 1\} \begin{bmatrix} \cos\Theta_{sw} & 0 & -\sin\Theta_{sw} \\ 0 & 1 & 0 \\ \sin\Theta_{sw} & 0 & \cos\Theta_{sw} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\Theta_{er} & \sin\Theta_{er} \\ 0 & -\sin\Theta_{er} & \cos\Theta_{er} \end{bmatrix}$$

$$= \{ \sin\Theta_{sw} , -\sin\Theta_{er} \times \cos\Theta_{sw} , \cos\Theta_{er} \times \cos\Theta_{sw} \}$$

Secondly, we calculate the unit drill vector U_d. This is a simple conversion from polar coordinates $\{ \Theta_{dp}, \Theta'_{az}, 1\}$ to cartesian coordinates,

$$U_d = \{ \sin\Theta_{dp} \times \sin\Theta'_{az} , -\sin\Theta_{dp} \times \cos\Theta_{az} , \cos\Theta_{dp} \}$$

Since the two vectors must be equivalent, $U_m = U_d$, yielding the following relationships:

$$\frac{U_m Y}{U_m Z} = \frac{U_d Y}{U_d Z}$$

$$\frac{\sin\theta_{er} \times \cos\theta_{sw}}{\cos\theta_{er} \times \cos\theta_{sw}} = \frac{\sin\theta_{dp} \times \cos\theta'_{az}}{\cos\theta_{dp}}$$

$$\tan\theta_{er} = \tan\theta_{dp} \times \cos\theta'_{az}$$

and

$$\sin\theta_{sw} = \sin\theta_{dp} \times \sin\theta'_{az}$$

This finally gives

$$\theta_{er} = \tan^{-1}(\tan\theta_{dp} \times \cos\theta'_{az})$$

$$\theta_{sw} = \sin^{-1}(\sin\theta_{dp} \times \sin\theta'_{az})$$

B.1 Calculation of IRS Deviation/Location

The most direct method of determining drill bit deviation is to obtain its position. At this time, no practical methods for doing this have been advanced. However, the relative position (deviation) may be tracked by knowing the direction vector of the drill bit and integrating as it progresses through the rock. Due to the limited bend of the pipe, this can be closely approximated by knowing the drill bit direction vector as each pipe is added.

Coordinate System

The coordinate system used is left-handed. For an operator standing at the drill hole, with the rig behind him, the positive x-axis extends to his left, the positive y-axis extends in front of him, and the z-axis extends upwards. Rotation about the x-axis R_x is called 'dip'. A positive R_x corresponds to the operator looking up, or a higher elevation of the positive y-axis. Rotation about the y-axis R_y is called `swing'. A positive R_y corresponds to the operator tilting to his left, or a drop of the positive x-axis. Rotation about the z-axis R_z specifies a change in bearing or heading. A positive R_z corresponds to the operator turning clockwise (see figure B.1.1).

One important reference for sensors is the gravity vector. It corresponds to the negative z-axis. Rotation about this axis produces no change in a gravity sensor. It is therefore independent of R_x and R_y, which do. R_x and R_y can be combined into a relative dip angle R_{xy} which defines the angle from the vertical, regardless of R_z, and corresponds to a cone of points. When combined with R_z, which defines a vertical plane of points, a single unique vector is specified.

Both the cartesian or polar coordinate systems can be used to

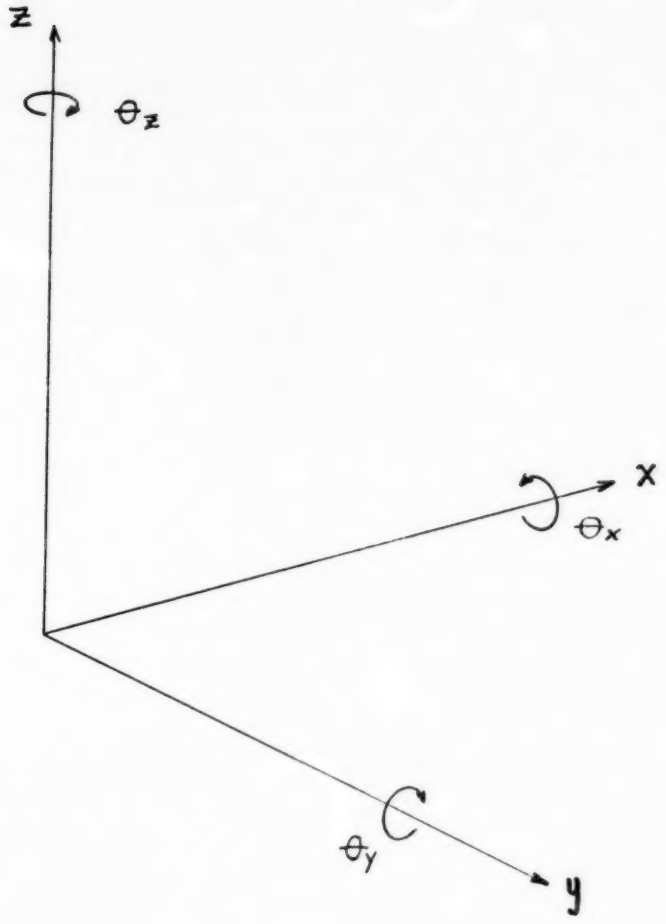


Figure B.1.1

Left-Handed Coordinate System

specify a drill vector or point. For the polar system, a vector is specified by

$$(R_{xy} , R_z)$$

and a point by

$$(R_{xy} , R_z , D)$$

where D is the distance of the point from the origin.

Calculation of Instrumented Rod Angles

The inclinometers in the instrumented rod rotate about the drill rod axis, Φ, which is at an angle R_{xy} from vertical. Assume the inclinometer is at a reference orientation, $\Phi = 0$, $R_{xy} = 0$ (vertical), and represent this orientation by the unit vector $U_I = \{ 0, 1, 0\}$. The output of the inclinometer is the angle between this vector and the xy plane,

$$\sin\theta_I = \frac{U_I z}{1} = U_I z$$

The transformations that the inclinometer undergoes as the drill string rotates at an angle from vertical can be described by a rotation about the z-axis of I , followed by a rotation about the x-axis of R_x.

$$U_I' = U_I [\Phi] [R_x]$$

$$= [0 \; 1 \; 0] \begin{bmatrix} \cos\Phi & \sin\Phi & 0 \\ -\sin\Phi & \cos\Phi & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos R_x & \sin R_x \end{bmatrix}$$

$$[\ 0 \quad 0 \quad 1\ ]\ [\ 0\ -\sin R_x\ \cos R_x\ ]$$

$$= [\ -\sin\Phi\ ,\ \cos\Phi \times \cos R_x\ ,\ \cos\Phi \times \sin R_x\ ]$$

and the angle $\theta_I = \sin^{-1}(\cos\Phi \times \sin R_x)$.

Since we have two inclinometers at right angles, there will be two readings

$$\sin\theta_1 = \cos\Phi \times \sin R_x$$

and

$$\sin\theta_2 = \cos(\Phi - 90) \times \sin R_x$$
$$= \sin\Phi \times \sin R_x$$

Combining the two expressions, we get

$$\frac{\sin\Phi \times \sin R_x}{\cos\Phi \times \sin R_x} = \frac{\sin\theta_2}{\sin\theta_1} = \tan\Phi$$

and substituting back into either equation we get the dip

$$R_{xy} = R_x = \sin^{-1}\left(\frac{\sin\theta_1}{\cos\Phi}\right) \qquad (1)$$

$$= \sin\text{-}1\left(\frac{\sin\theta_2}{\sin\Phi}\right) \qquad (2)$$

The form of the equation used will depend on the value of Rz to yield the best sensitivity. The form of the equation and its corresponding range of use is given below:

$$0 \leq \Phi < 45 \qquad (1)$$

45 ◀ Θ < 135 (2)

135 ◀ Θ < 225 (1)

225 ◀ Θ < 315 (2)

315 ◀ Θ < 360 (1)

Calculation of Deviation

The progress of the hole can be measured at the rig. This gives actual length of the drill steel. Due to drill string bending, this will be greater than the actual depth of the hole. At any point, the drill bit direction vector can be expressed as the two angles R_{xy} and R_z (see figure B.1.2). Given a rigid drill rod of known length L, then the position of the end point of the rod P relative to its start point is

$$P_x = L \times SIN (R_{xy}) \times SIN (R_z)$$

$$P_y = L \times SIN (R_{xy}) \times COS (R_z)$$

$$P_z = L \times COS (R_{xy})$$

In order to drill, the drill string is rotated along its long axis. The sensors within the drill rod will also rotate about the axis of the rod by some angle Ø. Due to the high vibration during drilling, it is anticipated that the drilling (and hence rotation) will be stopped while the dip and bearing measurements are taken. However, the angle of rotation at which the pipe stops will be random.

The drill string is assumed to have no twist, since it is not under load when the measurement is taken. Slip at the threaded coupling between rods is also assumed minimal since the rods are torqued to the full rig torque when joined. This allows the assumption that the instrumented rod will undergo the same rotation as that measured at the rig's rotary head. The angle of the rotary head is Ø' and is relative to the rig. The rotation of the drill rod about its axis Ø is measured relative to a 'home' orientaton of the drill rod, which is a function simply of the mounting of the sensors. When the instrumented rod is

attached, there will be a constant 'phase shift', ϕ_1, so that $\Phi' = \Phi + \phi_1$. This must be determined by measurement after the instrumented rod has been drilled and its orientation can be assumed to be equal to that of the mast. In addition, ϕ_1 must be updated everytime the drill string is broken and a rod added.

It is necessary to establish the relationship between the bearing of the instrumented rod, Φ, and Φ'. Assume that the rod is inclined at some angle of dip, bearing $R_z = \emptyset$, and for simplicity $\phi_1 = \emptyset$. Then $\Phi = \Phi'$. But the information from the instrumented rod, Φ and R_{xy}, only specifies anywhere on the surface of a cone formed as the rod is rotated about the z-axis. However, since the drill string is assumed not to twist, the change in R_z would cause an equal change in Φ'. Then the rotation angle at the rig is the sum of the roation of the drill string and the change in heading, $\Phi' = \Phi + R_z$. Therefore $\Phi + \phi_1 + R_z$, or

$$R_z = \Phi' - \Phi - \phi_1$$

At this point, R_z is relative to the rig. The absolute drill position can be calculated by using $R_z = \Phi' - \Phi - \phi_1 + \Theta_{rig\ az}$ and initiallizing the drill position to the known collar coordinates. Alternatively, relative position and bearing can be maintained, and simply converted to absolute position when the rig's position and azimuth is known.

Therefore a total of four variables are required to solve for incremental pipe position:

- D , length of drill rod
- R_{xy} , dip of drill rod
- R_z , bearing of drill rod

- Φ , rotation of the drill rod about its axis relative to a home orientation of the instrumented rod.

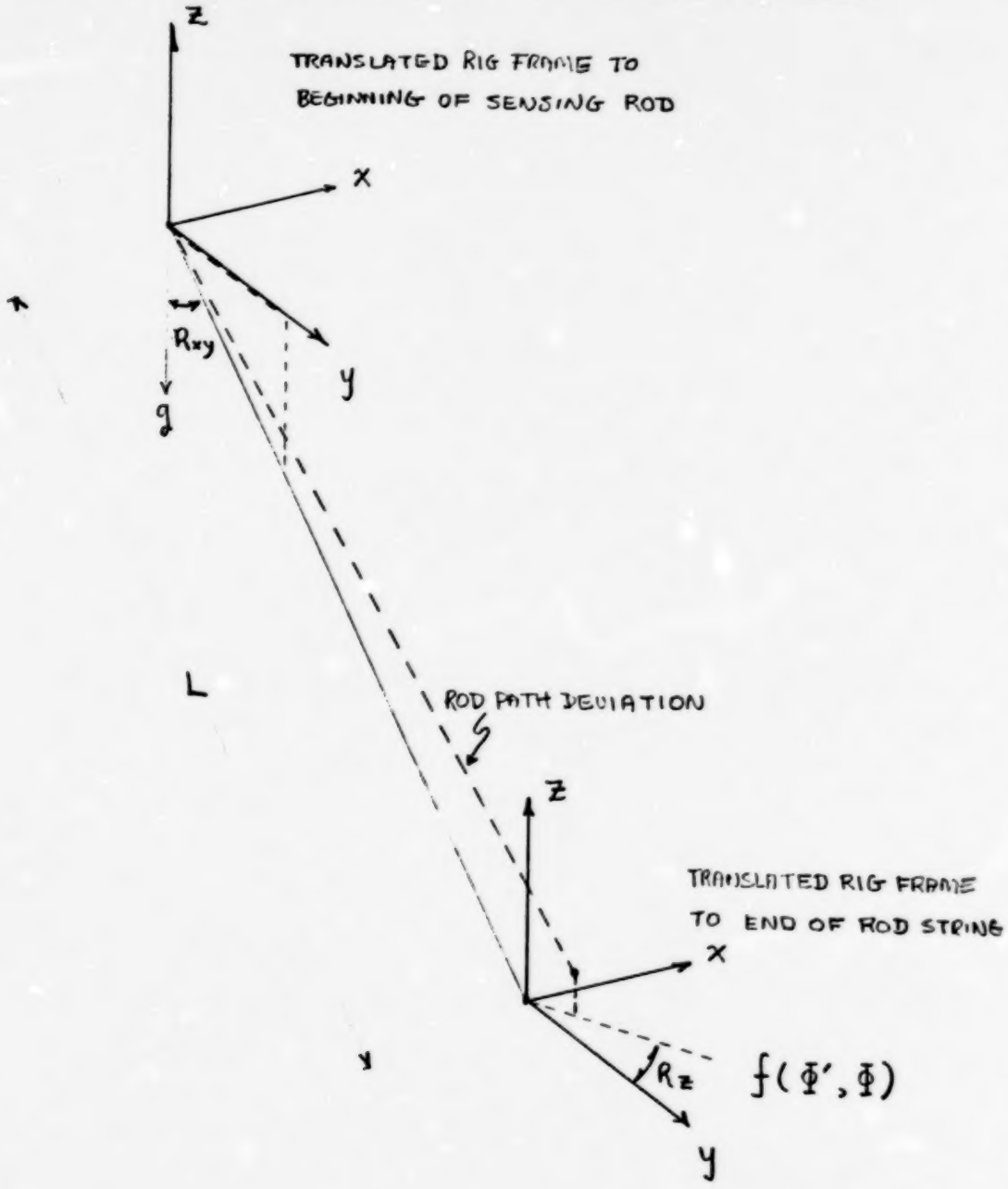


Figure B.1.2

Determination of Drill Rod Deviation

B.2 IRS Sensor Requirements

The purpose of the down-hole instrumentation package is to confirm that the actual drill hole is within a +/- 1% deviation of the intended drill hole. At the normal 200 foot depth, this corresponds to 2 feet, or +/- 0.57 degrees. It is required to measure the deviation to within +/- 5% error. This corresponds to an error of +/- 1.2 inches at 200 feet, or +/- 0.0286 total degrees.

The accuracy required of the sensors by these specifications depends on the types of error introduced by the sensors. Two of these are resolution and drift. Resolution error is not accumulative, i.e., the error of any given measurement is not dependent on the previous measurements. Drift error however is accumulative, since the error introduced by a given measurement must be added to the error of the previous measurements. For example, gravity sensitive devices such as inclinometers suffer from resolution error but not drift error since each measurement is taken relative to the fixed gravitation vector. Gyros however, are subject to drift error as well, since there is no fixed reference.

The non-accumulative error in deviation due to error in the measurement of R_{xy} after N pipes of L length is

$$E_{nRxyNa} = N \times L \times SIN(E_{Rxy})$$

For N=40, L=60, and a total error of 1.2 inches, E_{Rxy} = .0286 degrees.

The accumulative error in deviation due to error in the measurement of R_{xy} after N pipes of length L is

$$E_{nRxyAc} = \sum_{i=1}^{N} (L \times \sin(i \times E_{Rxy}))$$

$$= L \times \sum_{i=1}^{N} (\sin (i \times E_{Rxy}))$$

The following table shows the relationship between measurement error and total accumulated error for N=40, L=60:

measurement error(deg.)	total error(in.)
.00056	0.48 (1%)
.001	0.8597
.00280	2.4 (5%)
.0056	4.8 (10%)
.010	8.587

The error in deviation due to non-accumulative bearing measurement error is limited to the pipe 'zig-zagging' at an angle of 1/2 of the resolution error, instead of going straight. This quantity is

$$E_{nRzNa} = N \times L \times (1 - \cos (.5 \times E_{Rz})$$

and for N=40, L=60, and a maximum error of 1.2 in., E_{Rz} = 3.62 degrees.

Calculation of the deviation error due to accumulative bearing measurement error is more complex. Assume a pipe is proceeding along its trajectory with zero error and that $R_{xy} \neq 0$. However, due to drift in R_z the endpoint of the pipe is not at point Q but at Q', whose x-y position relative to its top point is

$$(Xd \times COS (R_z) , Xd \times SIN (R_z)).$$

After the process is repeated N times, the x-y position of the endpoint of the pipe will be

$$Q'_n = \left(\sum_{i=1}^{N} (Xd \times COS(i \times E_{Rz})), \sum_{i=1}^{N} (Xd \times SIN(i \times E_{Rz})) \right)$$

where $Xd = L \times SIN (R_{xy})$.

The measured deviation is therefore

$$SQRT \left(\left(\sum_{i=1}^{N} (Xd \times COS(i \times E_{Rz})) \right)^2 + \left(\sum_{i=1}^{N} (Xd \times SIN(i \times E_{Rz})) \right)^2 \right)$$

and the deviation error is

$$E_{nRzAc} = | Q_n | - | Q'_n |$$

$$= N \times Xd - SQRT\left(\left[Xd \times SIGMA (SIN (i \times E_{Rz})) \right]^2 + \left[Xd \times SIGMA (COS (i \times E_{Rz})) \right]^2 \right)$$

$$= L \times SIN (R_{xy}) \times \left(N - SQRT\left(\left(SIGMA (SIN (i \times E_{Rz})) \right)^2 + \left(SIGMA (COS (i \times E_{Rz})) \right)^2 \right) \right)$$

The following table shows the relationship between measurement

error and total accumulated deviation error, given N=40, L=60, and $R_{xy} = R_{xy\ max} = 51$ degrees:

measurement error (deg.)	deviation error (in.)
.1	0.378
.1125	0.48 (1%)
.1625	1.0
.252	2.4 (5%)
.3565	4.8 (10%)
.4167 (note 1)	6.56
1.0	37.6
1.25 (note 2)	58.586

notes:

1- 5 degs/hour @ 12 pipes/hour

2- 5 degs/hour @ 4 pipes/hour

B.3 Sensor Alternatives

Inclinometers

An inclinometer measures deviation from the gravitational force vector. The measurement can be along one or two axis. A two-axis inclinometer is capable of sensing tilt in any direction. If we align the Z-axis of a cartesian coordinate system with the gravity vector, the two-axis inclinometer will respond to both X and Y components of tilt, i.e., the tilt angle output is not sensitive to rotation of the device about the Z-axis. Theoretically, such a device could give us two pieces of information: the magnitude of the tilt; and, the direction of the tilt relative to some reference point on the device. An example of such a device is a planar bubble level, commonly used to level sensitive instrumentation. The bubble is free to move from center in any direction along the plane orthogonal to gravity. The distance of the bubble from center is a measure of degree of tilt, and the direction of movement is the direction of tilt.

The more common single axis inclinometer detects inclination only along a single plane. If we align the device along the X-axis, then tilt in the Y-axis will produce no output. Clearly as the device is tilted to 90 degrees, the sensitive axis is perpendicular to gravity, and a small tilt in the X-axis would produce a large and erroneous output. This is called cross-axis distortion, and is typically specified as the range of degrees over which tilt along the non-sensitive axis will effect the output by less than a specified maximum error. Two single axis inclinometers, if mounted at 90 degrees to each other (i.e., to sense X- and Y-axis tilt respectively), can generate after processing the same information as a two axis inclinometer. It is necessary that both devices are kept within their operating range in terms of output linearity and cross-axis distortion.

Processing of the signals can be used to extend the range and/or minimize error.

If we do not have an initial R_z reference point, so that R_x effectively becomes the absolute deviation R_{xy}, then solving Φ' will give us a pipe rotation angle relative to gravity only, and no bearing information can be extracted.

Tests have been performed with Sperry Accustar inclinometers. These units withstand rugged environments (up to 800 g's), a cross-axis error of less than 1 percent to 25 degrees (50 degrees typical), a time constant of 0.3 seconds, and a total range of +/- 60 degrees (with linearity corrections beyond +/- 45 degrees). Two types are available: analogue output at 60mv/degree, and digital (pulse width) output at .1 ms/degree. Maximum sample rate is 50 samples/second. Tests in actual drilling environment indicate that the mechanical sensor itself will survive the vibration and shock of drilling directly, but that the electronics will require some attenuation of the shock.

The use of inclinometers requires that the real rotation angle of the drill string be known. The rotation angle of the rotary head is known from the Drill Hydraulic Subsystem indexing angle sensor, but requires that the drill pipe already inserted NOT be disturbed during such operations as adding pipe segments, during which of course the drill pipe must rotate relative to the drive linkage. Disturbance to the drill pipe may have the following origins:

a) torsional stresses in the drill pipe due to binding against the wall of the hole are suddenly released causing the pipe at the top of the hole to rotate slightly. It has been shown this effect is minimal.

b) Many drill rigs have hydraulic "slip plates" for securing

the lower drill pipe while pipes are inserted/removed. When the slip plate is engaged, it may disturb the drill pipe in order to align with the flats. If the joint is broken (unthreaded) by this action, the drive linkage and angular transducer will not detect the error. If automatic control of pipe rotation and the slip plate is available, then the pipe could be rotated slowly until the slip plate engages fully. At that time the pipe's rotation is turned off, and the angular position of the pipe is recorded. When the slip plate is disengaged, the new angular position is also recorded and the difference from the initial position is used as an offset.

c) The Atlas/Copco drilling rig as well as the CMS CD-90 does not come standard with a hydraulic slip plate. Instead, a special wrench is manually slipped over the pipe flats and the pipe rotated until the wrench encounters either the left or right stop post, thereby preventing the rotation of the pipe in that direction. Even if this situation can be detected by additional sensors, it is necessary to know the dimensions of the wrench and that it be symmetrical. However, the majority of commercial rigs have some form of automatic breakout mechanism which can be used to ensure the pipe is locked during pipe addition and removal operation.

3.3 Compass (Magnetic North) Sensor

The ideal way to determine the pipe's bearing, or rotation angle R_z, is to house a sensor in the instrumented rod assembly capable of referencing itself to a frame of reference external to the rod. In most existing down-hole sensor packages this is done with a compass, a device capable of sensing the angle between its "home" orientation and the magnetic north pole. Solid-state compasses are available which provide the desired accuracy, have a small physical size and can survive high shock and vibration.

Due to the distance between the magnetic and astronomic North Poles, the compass reading taken from any point other than those along the "agonic" line (the meridian starting at the North Pole and passing through the magnetic North Pole) must be corrected by the compass declination for that area. The following additional problems are encountered in our application:

a) in order to sense the earth's magnetic field, it is necessary to house the sensor in nonmagnetic material. The length of nonmagnetic pipe required depends on the latitude of the site and on the sensitivity of the sensor. One commercially available product requires that a total of 55 feet of nonmagnetic pipe be used to guarantee a bearing error of less than 2 degrees when operating in moderate (Zone 1) magnetic latitudes. Additional length is required for higher latitudes. Since the instrumented rod assembly is limited to the length of one standard pipe (5-6 feet), use of a compass would require the development and use of special non-magnetic drill pipe ahead and after the instrumented assembly.

b) The ferrous content of the ore body for which this system is intended will greatly distort the earth's magnetic field, leading to considerable errors in bearing.

Another approach is to use a compass to sense relative magnetic north heading rather than absolute. What is required is the heading of the drill bit relative to an initial "home" heading, established when the first sensor reading is taken, for example. If the distortion of the magnetic north direction is reasonably constant throughout the length of the hole, then it would be possible to sense the pipe's rotation R_z.

At this time, it is not known how much the ore body attenuates the earth's magnetic field, and whether the distortion is constant for the length of a drill hole.

3.4 Gyros and Rate Gyro Pipe Rotation Tracking

A gyro is used to provide an absolute reference inertial frame. By spinning a mass at high speed and suspending it in very low friction mountings, the law of conservation of angular momentum will maintain the orientation of the plane of rotation. Deviations of the gyro casing from this plane can be precisely detected. Two gyros with orthogonal axis of spin can be used to detect tri-axial angular displacement relative to the inertial frame in which the gyros were initialized. A single gyro could also be used to sense θ. Gyros small enough to fit within the instrumented rod assembly envelope are available. However, they are sensitive mechanical devices that do not withstand much shock or vibration. By using sufficient shock mounting of the instrumentation package, it becomes possible to use some commercially available gyros built for the mining environment. They can withstand some degree of shock and vibration and have a very low drift rate for their size of less than 5 degrees per hour. Assuming a drill rate of 15 minutes per pipe, or 4 pipes per hour, the maximum drift error per pipe could be as high as 1.25 degrees. Assuming the gyro is used to track R_z, the accumulation error calculations indicate this corresponds to 58.6 inches, which is clearly unacceptable.

A different approach is top use rate gyros. These devices produce an output proportional to their absolute rate of rotation about an axis. Three orthogonaly mounted devices can be used to detect rotation about any axis. Rate gyros are typically more robust than true gyros. Some common principles of operation are:

i) measurement of the centrifugal force exerted by a mass as it is rotated about axis of rotation.

ii) measurement of fluid flow around a closed loop, caused by centrifugal forces.

iii) laser gyro measures the frequency shift of light caused by rotational velocity of the laser.

iv) quartz vibratory type measures the magnitude of the relative rotational vibration of a rotating vibrating tuning fork.

The output of the rate gyro must be integrated to yield angular displacement. This process effectively limits the accuracy of the technique since any errors are also integrated. A rate gyro might be used to track R_z at the down-hole instrumented assembly. It would be necessary to constantly sample and integrate the output, even while drilling.

It is difficult to limit error with an analogue integrator. The alternative is to sample and convert the output to digital and integrate numerically. The errors introduced by digital integration are: quantization error caused by the finite number of bits used to represent the analogue output; and, sampling error caused by the finite sampling rate.

One vibratory rate gyro is available with maximum input rates of 1000 degrees/second, and resolution of .004 degrees/second, or 0.0004 % of full scale. Sources of error are more likely to come from factors such as: a random drift of .05% of full scale; a turn-on scale factor repeatability error of less than .1 % of full scale; a g-sensitive drift of 0.04 degrees/second/g which effectively means that unless vibration is well damped, a sizeable error is introduced; and, an output noise level of 0.2 degrees/second RMS. Assuming digital integration with 16 bit resolution, 10,000 samples/second sample rate, and first order approximation, digital integration error will be small compared to other sensor signal errors. If ζ is a constant error in the rate signal in degrees/second, then the total error is the integral of the error over the time required, which is equal to

the product of the constant error and the time. Using a maximum allowable error of 10 degrees and a time to drill 200 feet of 10 hours or 36000 seconds, then

$$\frac{z}{z}\ (36000) = 10$$

$$\frac{z}{z} = .00028 \text{ degrees/second or } .00002 \text{ \% of full scale}$$

The rate gyro specified above (the best available at this time) cannot meet these requirements. Clearly a rate gyro cannot be used without periodic realignment.

3.5 Accelerometer

An accelerometer is used to measure the acceleration force along an axis, and is insensitive to rotation about that axis. Three orthogonally mounted sensors can be used as a two-axis inclinometer, but with no cross-axis distortion (other than that inherent in the devices and their mounting) and no range limits. It can provide essentially the same information as the inclinometer sensors.